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Comparisons of Hydrogeologic Modeling Methods to Define Capture Zones for Public Water Supply Wells in Northern Arkansas

Paula Anderson
University of Arkansas, Fayetteville

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Paula Anderson
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Dr. Ralph Davis
Thesis Director

____
Dr. Doy Zachry
Committee Member

____
Dr. Matthew Covington
Committee Member

ABSTRACT

The usefulness, applicability, and practicality of more complex and resource consuming methods for groundwater modeling has been in question since computer based groundwater modeling was established (Anderson, 1992). In many situations, computer modeling of groundwater flow is a necessity and useful for extrapolating data where none exists or it is impossible or impractical to acquire. However, when delineating a recharge area around a public water well for protection purposes, it is unknown if more detailed computer modeling results are better than simpler hydrologic calculations and site study. In the case of public drinking water supply wells located in various aquifers and with differing hydrodynamic processes, it may be useful to examine specific supply wells that have reasonable data. Then utilize a variety of modeling methods to fully analyze well hydrodynamics. By utilizing a variety of models for a few wells that have the best available hydrologic data, it can be determined whether complex and in depth modeling methods are warranted. This more specific information can then be extrapolated to other similar water supply wells to provide the most practical and economical methodology for groundwater modeling.

It was discovered in this study that computer modeling did prove to be useful and effective when surface water influence of the water supply well may be occurring. The computer model provided detailed information on how the aquifer responds when a pumping supply well is present in close proximity to a surface water body. The computer modeling was also able to indicate that a water supply well was not under influence of a nearby surface water body which is equally important when capture zones are being established for protection purposes.

Computer modeling of deeper wells, without the potential of surface water influence, proved less useful. Results from computer modeling and analytical models were highly varied,

even when similar input values were utilized. Results were more questionable and less accurate in determining proper capture zones. The delineation of capture zones can be established fairly well utilizing analytical models. Some analytical model results did give a much smaller radius of influence than was determined by the computer model. However, it ultimately falls to the regulatory agencies to determine what extent of protection for a wellhead is deemed appropriate and feasible.

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I would like to thank Dr. Ralph Davis for all of his patience, support, and willingness to assist me in this endeavor. Thanks also to my committee members, Dr. Doy Zachry, and Dr. Matthew Covington. I greatly appreciate all the professors in the Geoscience Department who made learning such a joy. Appreciation also goes to past and present staff of the Arkansas Department of Health and the Arkansas Geological Commission who gladly provided information and assistance for completion of this thesis.

DEDICATION

To my kids, husband, parents, and family, I could not be more blessed and fortunate to have you all in my life! Thanks for all the sacrifices you made so this can come to fruition.

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I. INTRODUCTION

A bountiful and clean public drinking water supply is perhaps one of the most underappreciated providers of life and well being. Following any major natural or manmade disaster, the availability of clean drinking water is essential above all else for people's survival. However, a public water system's future viability can be easily overlooked until it is consumed beyond its capacity or it becomes contaminated. In the United States of America the Safe Drinking Water Act Amendments of 1996 (U.S. EPA 1997) outlined programs to promote the protection of America's public drinking water supplies. Water that can potentially become public drinking water is known as source water. The Source Water Assessment Program (SWAP) was one program that directed assessment of the nation's drinking water supplies.

The Safe Drinking Water Act Amendments directed the U.S. Environmental Protection Agency (EPA) to be responsible for oversight of the SWAP implementation in each state. In Arkansas, the EPA delegated authority to the Arkansas Department of Health (ADH) to complete the SWAP (ADH SWPP 2014). The purpose of the SWAP is to determine source water areas and delineate those areas for further assessment and protection. The assessment is a tool that examines the potential for detrimental impacts from sites within the source water area. The assessment information can be utilized to develop protection methods, best management practices or future municipality zoning. They are also used as a tool to promote public awareness and understanding.

In Arkansas there is a wide range of source water that includes rivers, lakes, springs, and wells that provide groundwater. The ADH has utilized a variety of methods for determining source water protection areas depending upon the source water type and other considerations.

For groundwater wells the ADH has utilized multiple methods for determining source water or wellhead protection areas (Cordova 1999 and CAST 2001) and making assessment area delineations. One method is by using simple calculations based on the Theis nonequilibrium formula that determines a fixed radius. The fixed radius is centered on the wellhead and a circular source water delineation area is established. In other circumstances a simple predetermined fixed radius is utilized for wells and is based on generalized hydrologic properties. The EPA has advised that these fixed radius source water delineations are sufficient and useful where hydrologic data may be scarce. When a water supply well is examined by ADH they may determine that surface water could have a direct impact on the groundwater. These are called 'ground water under direct impact' or GWUDI wells and these wells typically have their entire watershed delineated as the wellhead protection area.

Wells may be identified as GWUDI wells by the ADH for a variety of reasons. Wells constructed in the middle to early part of the 1900's often have unknown construction details. As with many things, construction details for a well may be lost to the ravages of time if they were even recorded in the first place. The budget and personnel constraints of a small municipality make it difficult to investigate well construction details when they are unknown. Without construction information the worst case scenario must be assumed in order to adequately protect the well. A well that lacks proper grouting or casing could be directly impacted by surface water. Also, in areas with karst or fracture flow, a poorly cased or grouted well may in effect draw water from underground streams which can be linked to surface water. In these situations, where a potential direct link between surface and groundwater is present, any up gradient surface water containing potential contaminants can contribute water to the supply well. Thus the entire upgradient watershed becomes the source water delineation area.

The ADH and other entities have questioned the validity, usefulness, and applicability of fixed radius delineations for source water protection for ground water wells. These source water protection areas can have important impacts on local land use. Municipalities may decide to utilize the information when creating zoning regulations. Proper zoning could provide protection from future use that could have detrimental impacts. However, if the protection area is excessively large or appears misguided, a municipality and citizens may be less likely to take steps to protect their water quality.

In many cases there is a large safety factor incorporated into the radius calculation determination. This may be good to insure that all of a recharge area is adequately protected but can generate excess assessment of potential contaminant sources. More significant and hazardous potential or active impacts could get lost among the superfluous data. Due to the ongoing desire of the ADH to provide the best assessment area delineation for water supply wells they have questioned whether more complex computer calculations and modeling coupled with extensive site research can yield more appropriate source water delineations for water supply well protection.

SWAPs in other states have used various methods for water supply well source water delineations. Some states adopted a fixed radius assessment area or analytical methods with time of travel boundaries (Washington, 2010), while others utilized various computer modeling programs. EPA developed two computer modeling programs WHPA and whAEM 2000 (EPA, 2014). The WHPA program is a DOS based program and was mentioned sporadically by state SWAPs for delineation purposes. Also, a few states mentioned using whAEM as an assessment tool in their preliminary SWAP plans (Nebraska, 2014). However, there are scant examples of delineations that were generated from the EPA model programs. As the SWAP plans are simply plans, many methods mentioned in the individual plans never came to fruition. Some states such as Idaho did extensive work on their SWAPs and utilized a refined analytical model and numerical modeling.

The usefulness, applicability, and practicality of more complex and resource consuming methods for groundwater modeling has been in question since computer based groundwater modeling was established (Anderson 1992). In many situations, computer modeling of groundwater flow is a necessity and useful for extrapolating data where none exists or it is impossible or impractical to acquire. However, when delineating a recharge area around a public water well for protection purposes, it is unknown if more detailed computer modeling results are better than simpler hydrologic calculations and site study. In the case of public drinking water supply wells located in various aquifers and with differing hydrodynamic processes, it may be useful to examine specific supply wells that have pertinent hydrologic data which can then be applied to other wells. Then utilize a variety of modeling methods to fully analyze well hydrodynamics. By utilizing a variety of models for a few wells that have good hydrologic data, it can be determined whether complex and in depth modeling methods are warranted. This more specific information can then be extrapolated to other similar water supply wells to provide the most practical and economical methodology for groundwater modeling.

The ADH has expressed interest in a study to establish best methods for delineating wellhead protection areas. They have provided information on several municipal water systems. As the information for the Holiday Island water system is the most complete and contains multiple water supply wells, it has been selected for study. For comparison, Calico Rock water system has been selected which also contains multiple water supply wells and more accurately represents the all too common problem of long lost or incomplete well information and data.

General locations of the two study areas can be seen in Figure 1.

Figure 1. General locations of Holiday Island and Calico Rock in Northern Arkansas (Google Maps 2014)

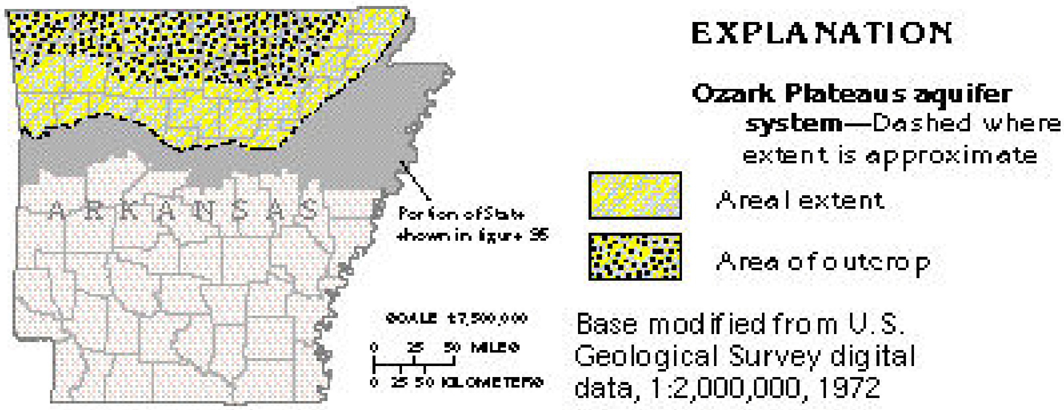
II. BACKGROUND INFORMATION

The Holiday Island and Calico Rock water systems draw water from the Ozark aquifer. The extent of the Ozark aquifer across northern Arkansas can be seen in Figure 2 and the stratigraphy of the Ozark aquifer in Arkansas can be seen in Table 1. The stratigraphy presented in Table 1 as presented by Schrader, (2004) does not list the Gunter Member of the Gasconade Formation. The Ozark aquifer is confined regionally at its top by the Chattanooga Shale (Ozark confining unit) but the Chattanooga is absent at both the Holiday Island and Calico Rock water system locations. The composition of Ordovician rocks in the Ozark aquifer is highly varied and very discontinuous (MacDonald 1977). The rock types include limestone, sandstone, dolostone, chert and minor amounts of shale with various mixes and interbedding of all of these rock types. The complex stratigraphy of the Ordovician sequence of rocks does not have any reliable diagnostic bed markers to differentiate some geologic units but certain formations can sometimes be identified (MacDonald, Zachry, & Jeffus 1977). The only method for accurately identifying stratigraphic formations of Ordovician age is by microscopic examination of rock from well cutting samples. Well cutting samples are collected by the well driller while the well is being drilled. The validity of the stratigraphic locations relies upon the well driller to accurately collect and log sample information while drilling is occurring. Due to the lack of ability to accurately differentiate geologic units and hydrologic formations, calculations must be made based on the entire open and saturated rock strata present in the well borehole.

Table 1. Stratigraphic column with descriptions of lithologic and geohydrologic properties of Ozark aquifer within Arkansas (Schrader 2004).

ERA	PERIOD	GEOLOGIC UNIT	GEOHYDROLOGIC UNIT	LITHOLOGY	THICKNESS (feet)	GEOHYDROLOGY
Paleozoic	Devonian	Chattanooga Shale	Ozark confining unit	Shale unit that crops out in a narrow band that outlines the Ozark aquifer and is missing where the Ozark aquifer is exposed at the surface.	0 - 200	Unit is relatively impermeable because of large shale content.
		Clifty Limestone	Ozark aquifer	Chert with lenses of limestone, dolomite, and cherty sandstone.	0 - 250	The residual cherty rubble, weathered from cherty limestone and sandstone of the unit, may yield 2 to 5 gallons per minute.
		Penters Chert				
	Silurian	Lafferty Limestone		Limestone, dolomite, sandstone, and minor amounts of shale	0 - 2,000	The limestones and dolomites commonly yield 5 to 10 gallons per minute from solution channels, bedding planes, and fractures. Similar yields may be obtained from the sandstone where it is porous or fractured. These units contain many springs. Yields from springs and some wells may exceed 50 gallons per minute.
		St. Clair Limestone				
		Brassfield Limestone				
	Ordovician	Cason Shale				
		Fernvale Limestone				
		Kimmswick Limestone				
		Plattin Limestone				
		Joachim Dolomite				
		St. Peter Sandstone				
		Everton Formation				
		Smithville Formation		Dolomite, dolomitic limestone, and minor amounts of sandstone and shale.	100 - 1,000	The solution channels and fractures in the dolomite and dolomitic limestone commonly yield 5 to 10 gallons per minute. Wells that tap large solution channels may yield more than 50 gallons per minute, but large yields are uncommon. These units yield water to several large springs.
		Powell Dolomite				
		Cotter Dolomite				
		Jefferson City Dolomite				
		Roubidoux Formation		Sandstone and sandy dolomite. Not exposed in Arkansas.	100 - 250	Yields of as much as 450 gallons per minute may be obtained from some wells, but yields are highly variable and generally average less than 150 gallons per minute.
		Gasconade Dolomite		Dolomite, sandy dolomite, and sandstone. Not exposed in Arkansas.	350 - 650	The most productive water-bearing part of this unit is the Van Buren Formation. Wells that tap into the Van Buren Formation commonly yield 150 to 300 gallons per minute and may yield as much as 500 gallons per minute.
		Van Buren Formation				
	Cambrian	Eminence Dolomite				
		Potosi Dolomite				
		Doe Run Dolomite	St. Francois confining unit	Shale and shaley dolomite, siltstone, and limestone conglomerate. Shales present both as distinct beds and disseminated throughout dolomite matrix. Not exposed in Arkansas.	0 - 750	Permeability is minimal to moderate. Unit is more permeable where transected by fault and fracture zones.
		Derby Dolomite				
		Davis Formation				

Figure 2. Extent of Ozark aquifer (Renken 1998)



The Ordovician and older Cambrian age rock strata outcrop in southern Missouri and dip southward 0.5 to 2 degrees between 46-184 ft per mile in northern Arkansas (Prior et. al. 1999). Cambrian formations were subjected to repeated uplifts with the Ozark dome being the most dominant structural uplift feature and subsequent movement has propagated from older fault lines. Additionally, normal faulting in the Springfield Plateau occurred in response to the Ouachita Orogeny (Arbenz 1989). The major faults are oriented northeast-southwest and their associated orthagonal fracture and joint patterns control the groundwater flow (Davis et.al. 2000). Recharge of the Ozark aquifer occurs where the formations are exposed in Missouri and directly by interformational movement. Regional groundwater movement typically follows surface topography and flows towards groundwater troughs which correspond to deeply incised drainage basins. Some sections of rock strata act as local aquitards while others have limited artesian properties.

Yields of the Ozark aquifer show large variations due to the processes that have affected the permeability of the strata (MacDonald Zachry & Jeffus 1977). Dissolution of the carbonate formations has left interconnected vugs and enlarged openings for ground water movement along bedding planes and fractures. Wells in the Ozark aquifer yield 20 to 600 gallons per minute with no predictable pattern to the yield rates (Prior et. al. 1999).   The discontinuous occurrences of high yield areas suggest that rock characteristics which determine water production are not heterogeneous in their subsurface distribution. Well yield variability can be due to structure, faulting, solutioning, aquifer thickness, well construction details, and changes in the lithic character of the rock. Differences in cementation, grain size, or dolomitization directly affect porosity and permeability. Comparisons between the relatively high yielding Holiday Island wells and low yielding Calico Rock wells are supportive of this analysis.

Most reports about the Ozark aquifer focus on the Roubidoux and Gasconade Formations because they sometimes have significantly higher yields than the Cotter or Jefferson City Formations. However, well construction and ADH reports for the study areas indicate that a significant supply of water must be coming from the Cotter and Jefferson City Formations. It also should be noted that shallower domestic wells in the Ozark aquifer typically don't reach the deeper Roubidoux or Gasconade Formations, but do supply ample water for domestic use. The deeper municipal wells or wells drilled for businesses or industries that reach the deeper formations do have a more dependable water supply since the deeper formations are moderately artesian in nature (MacDonald Zachry & Jeffus 1977). Many previous investigations into the deeper strata of the Ozark aquifer don't assess shallower portions as being significant contributors to the overall yield of the aquifer system. A study of the wells of the Calico Rock water system indicates that where the overall aquifer system is lower in yield the shallower Cotter and Jefferson City Formations contribute a higher proportion of the total well yield.

One of the first reports written about the Ozark aquifer is titled *Northern Arkansas Groundwater Inventory* (MacDonald 1977). This report contains hydrogeologic information about specific wells across the Springfield Plateau in northern Arkansas and Southern Missouri. Holiday Island wells one and four are included in the assessment with pump test results and calculated hydrologic properties. Information from this report is included in a report titled *Summary of Aquifer Test Data for Arkansas—1940-2006* (Pugh 2008). The report by Pugh contains more information about additional wells which are listed by county and aquifer formation. There are no data available specific to the Calico Rock wells in any of the reports assessed. However, the *Summary of Aquifer Test Data for Arkansas—1940-2006* report does give information about one well in the same county as the Calico Rock wells and multiple wells in Stone and Baxter counties which are adjacent to Izard county. Data from wells near Calico Rock were assessed to find wells with similar yields, construction details, and aquifer properties.

Wellhead protection areas have been calculated for all the wells at Holiday Island and Calico Rock. Initially Bob Cordova conducted the study for delineation of the areas when he worked for the Arkansas Department of Health (Cordova 1992 1999 & 2000). More recently the ADH determined a new protection radius for each wellhead, which is listed in Sanitary Survey reports (Holt 2012, Taylor 2013). In addition to the wellhead protection area reports and Sanitary Survey reports, Metered Water Usage Reports were provided for each water system. The Sanitary Surveys also supply answers to the questions: "Does the system have an active source water protection program? If yes what control measures are in place?" Both Holiday Island and Calico Rock have source water protection programs in place. The wellhead protection radii for both the Holiday Island and Calico Rock wells are 100 feet or less and the ADH reports state that source water protection program control measures are by "Ownership of WHPA (well head protection area)".

Bill Prior of the Arkansas Geological Survey examined well cutting samples from more recently constructed wells in the study areas and created strip logs with interpolations of geologic formations. The strip logs are included in this thesis and were utilized with other logs to determine aquifer characteristics that were published in the report *Roubidoux Formation and Gunter Sandstone Member of the Gasconade Formation, Major Aquifers in northern Arkansas.* (Prior et. al. 1999). The strip logs were compared to well construction reports to determine if correlations can be made so that formations might be interpreted for wells that only have well construction report information.

A. BEAVER LAKE DAM WELL

The interplay between stratigraphy, structure, dissolution, and hydrodynamics of the Ozark aquifer can be illustrated by examination of a particular well located near the Beaver Lake dam. This well is approximately seven miles southwest of Holiday Island and well construction report information can be seen in Table 2 with an actual copy of the construction report located in Appendix A. The well was drilled below the dam of Beaver Lake to provide water for a Corp of Engineers public campground. At one point during well construction in 1988, an aquitard was penetrated and a tall water spout formed. Artesian flow then subsided to a rate of 14 gallons per minute. The well is currently being utilized by the public campground and has maintained its artesian flow.

Table 2. Well construction information for Corp. of Engineers well located near Beaver Lake dam.

Well owner: Corp of Engineers			
Location: SE1/4 NW1/4 Sec 2 T20N R27W	Depth in feet		
Well completed 7/18/1988	From	To	Formation
Well produces 150 gallons per minute	0	26	Overburden
Well artesian flow 14 gallons per minute	26	553	Dolomite
Cased and grouted from 0 to 206 feet with 6.65 inch casing	553	630	Roubidoux

The artesian nature of the well and the nearby constant head source of Beaver Lake creates a more thorough picture of the hydrogeology of the area. As the well is cased and grouted to a depth of 206 feet, there must be a rock layer or series of layers which act as an aquitard in the immediate area of the wellhead and dam. A fault or fracture also must be present under or near Beaver Lake to facilitate the hydraulic head pressure that causes the artesian flow of the well. Because of the hydraulic head pressure, lake water may be forced directly through solutionally enlarged faults to lower bedding planes in the deeper rock formations. However, the conduits in the rock formations below the cased depth of the well must be somewhat discrete in nature. According to the well construction report the well yield is only 150 gallons per minute and the artesian flow rate is only 14 gallons per minute. Neither flow rate is excessive considering the well has 424 feet of open borehole available for recharge. For comparison, a six inch diameter pipe can transmit 200 gallons per minute with a velocity of only two feet per second and pumps designed for six inch diameter wells can have pumping rates up to 500 gallons per minute (personal communication with Mr. Robert White, PE). The yield is also much lower than water supply wells at Holiday Island which each yield 400 gallons per minute or more.

B. HOLIDAY ISLAND WATER SYSTEM

There have been seven water supply wells drilled for the Holiday Island waterworks between 1970 and 1984 as documented in the well construction reports in Appendix A and ADH reports (Cordova 1999, Holt 2012, Kort 2013). The wells range in depth from 1,063 feet to 1,880 feet as documented in well construction logs, ADH, and Arkansas Geological Survey (AGS) information. Well nomenclature has varied throughout different reports but this seems to be due to errors in well location identification. For the purposes of this thesis they are sequentially identified as HI 1 through HI 7. Extensive research was done to determine locations of the wells from well construction reports, coordinates, and directions given in ADH reports. Location information was then correlated to the individual wells. Holiday Island waterworks currently only utilizes three wells for municipal production as documented in the ADH Sanitary Survey (Holt 2012). Well HI 3 was capped for future use after completion. Well HI 2 is currently inactive due to high levels of radium. Wells HI 6 and HI 7 were drilled most recently and are utilized for irrigation purposes according to ADH and Well Construction Reports. The location information for wells HI 3 and HI 6 is limited to township, section, and range. There is no other documented well location information for utilization in determining more exact wellhead location. Thus, wellhead elevations for HI 3 and HI 6 are unknown. The wells have a minimum of 500 feet of well casing and grouting with the exception of the irrigation wells which have shorter casing lengths. The wells provide an ample water supply to the system with each well yielding between 430 and 600 gallons per minute (Cordova, 1999 and Holt, 2012). However, due to water loss of 72% in the distribution system of the total pumped water for the system, they sometimes have difficulty meeting demand. The system in 2013 requested that the

ADH allow the irrigation well HI 7 to be utilized for municipal water purposes. Information about HI 7 was gathered from a memo supplied by the ADH and a strip log supplied by the AGS.

Locations from latitude and longitude listed on the 2012 Sanitary Survey were compared to section, township, range listings and other given directions on the well construction reports to correctly identify and correlate information. After study and comparison between the various ADH and well construction reports, it has been determined that the ADH reports contain inaccuracies regarding the individual well information. The 2012 Sanitary Survey has the wrong date drilled and total depth listed for Well 1-01. The total depth listed for Well 2-02 is also incorrect. There are two well construction reports for Sec. 23 T21N R26W which could both be Well 5-04 based on location directions in the Sanitary Survey. One of these wells is the most recently constructed well that is utilized for irrigation purposes and is named HI 6 in this thesis. Construction details for Well 5-04 that are listed in the 2012 Sanitary Survey do not correlate to information on either the HI 5 or HI 6 construction report. The "Wellhead Protection Program Phase 1: Delineation of the Wellhead Protection Area for Holiday Island" reports in Table 1 that Well 4(5) is a well that was constructed in 1984 to a depth of 1,255 ft. which corresponds to the construction report for HI 6, the irrigation well. However, there are errors in Table 1 that include the wrong section number, total well depth and casing diameter listed for Well 2(4). Also, well number 4(5) should be the 1,880 ft. deep well with corresponding data and well 5(3) should be HI 5 with a total depth of 1,184 ft. The locations of the wells are labeled correctly on the wellhead protection area delineation map.

Wellhead protection areas for the Holiday Island wells were determined in 1999 by the ADH as reported in the "Wellhead Protection Program Phase 1: Delineation of the Wellhead Protection Area for Holiday Island" by Bob Cordova. It was determined that the protection areas would be fixed radius areas centered on the wellheads. The radius distance for each well varied from 2,000 to 2,800 feet depending upon well specific inputs to the Theis nonequilibrium formula. In the 2012 Sanitary Survey, a protection radius of 100 feet is given on each individual well's source information table.

Although not all of Holiday Island's wells are in production, the construction logs for the unused wells with hydrologic information can be useful for investigating the lithology and hydrology. Additionally, it may be feasible to compare the stratigraphy of all the well logs to determine trend of rock beds. The alignment or incongruity of rock formations between wells can be used to extrapolate potential faulting and determine fault offset. If evidence for faulting is found then the potential impact to the hydrology of the area will need to be investigated.

Select data for the Holiday Island wells are documented in Table 3. The well construction records for wells HI 4, HI 5, and HI 6 included cutting description logs provided by the driller. Well construction reports for all the Holiday Island wells are located in Appendix A with the exception of HI 7. Information regarding HI 7 was documented in an ADH report. Cutting samples from HI 7 well were sent to the Arkansas Geological Survey (AGS) and Mr. William Prior of the Arkansas Geological Survey studied them and generated a strip log for the well (Figure 3) which has been condensed into Table 4 and lists formations and depths. The driller's log of rock information for wells HI 4, HI 5, and HI 6 are located in tables 5, 6, and 7 respectively. Well construction reports for wells HI 1, HI 2, and HI 3 indicated that the samples and description were on file with or sent to the Arkansas Geological Commission which later became the Arkansas Geological Survey. An inquiry was made to staff at AGS regarding the missing well construction log information. Staff at AGS were unable to locate descriptions, however, the cutting samples are most likely warehoused with other samples at the AGS warehouse location.

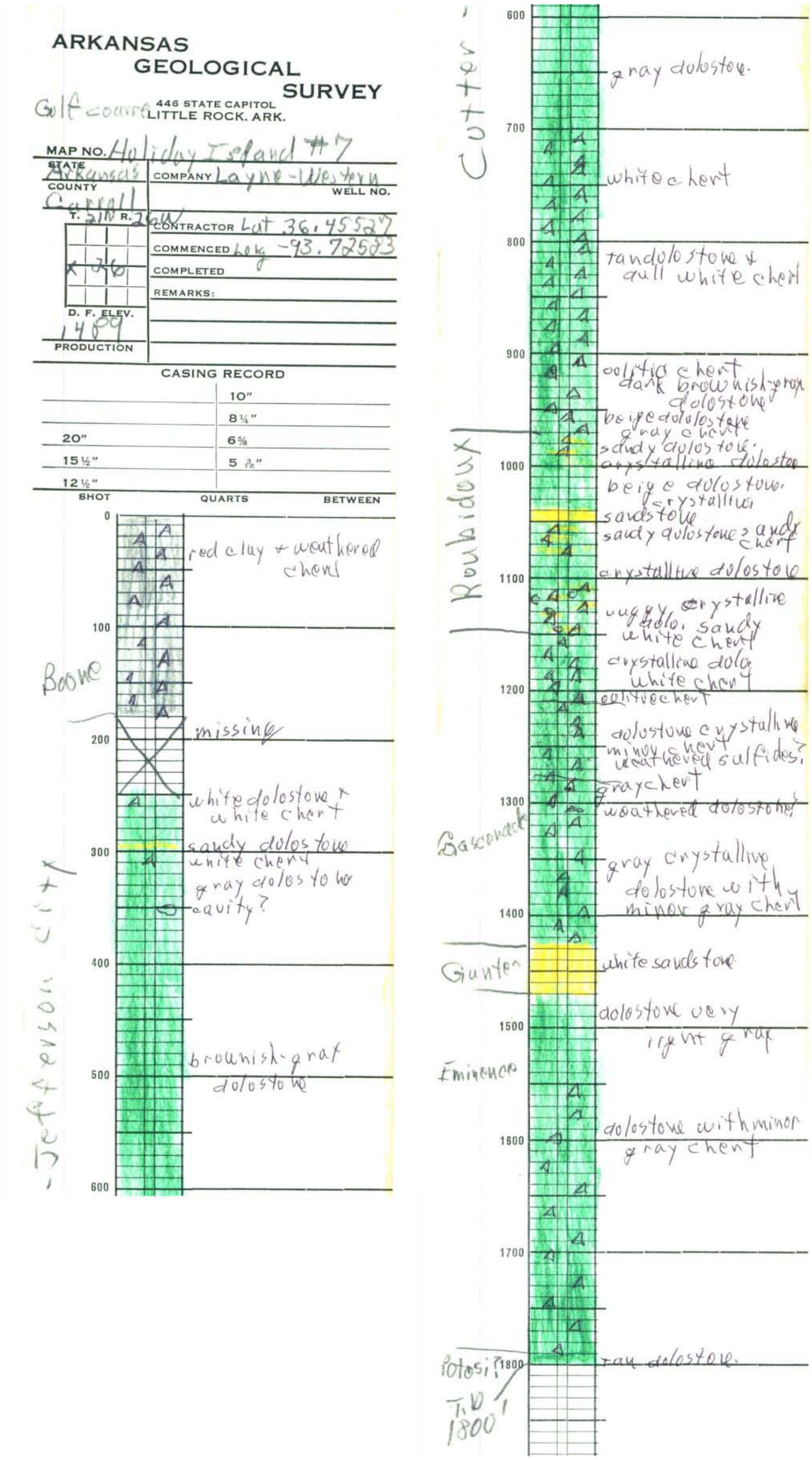
Table 3. Well construction information for Holiday Island Wells. Well yield and depth to water are listed as a range when available reports from different times give various data.

Well ID	Depth ft.	Completion date	Depth to Water Level ft.	Casing Diameter in.	Casing Depth ft.	Grout Depth ft.	Elevation	Well Yield
HI 1	1063	12/15/1970	42-100	8	500	500	1010	400-600
HI 2	1128	12/18/1970	60-137	8	500	500	1100	500
HI 3	1270	10/5/1971	unknown	8	500	500	unknown	400
HI 4	1880	6/15/1972	520	13	513	513	1530	500-550
HI 5	1184	6/23/1977	146	11	500	500	1110	430-500
HI 6	1255	10/7/1984	253	16	20	20	unknown	500
HI 7	1800	2004	504	12	390	390	1490	500-520

Table 4. Well strip log information for HI 7 from William Prior of Arkansas Geological Survey.

Depth in Feet					
From	To	Thickness	Formation	Elevation at top of formation ft.	Elevation at base of formation ft.
0	180	180	Boone	1490	1310
180	250	70	missing	1310	1240
180	970	790	Jefferson City/Cotter	1310	520
970	1150	180	Roubidoux	520	340
1150	1430	280	Gasconade	340	60
1430	1470	40	Gunter	60	20
1470	1790	320	Eminence	20	-300
1790	1800	10	Potosi	-300	-310

Figure 3. Strip log generated from well cuttings from HI 7 well construction provided by William Prior of Arkansas Geological Survey.



The strip log from well HI 7 was completed in a laboratory setting at AGS utilizing microscopic analysis of the cuttings by Bill Prior. The microscopic analysis was completed to accurately identify the correlating rock formations. The clarified and condensed interpretation of the strip log is presented in Table 5. Well HI 7 is located within approximately 500 feet from well HI 4 and comparison between Tables 4 and 5 indicate that there is little correlation between the well driller's description and the strip log. Changes in description do not definitively correlate to any formation changes based on the depths listed in the two documents. This discrepancy would indicate that descriptions from the well driller's construction reports cannot be used effectively to interpret geologic formations.

Table 5. Well construction report rock cutting samples description by depth for HI 4.

Depth in Feet				
From	To	Description	Thickness	Elevation of unit top in ft.
0	15	red clay w/ white chert bolders	15	1530
15	150	broken chert w/ red & brown clay seams	135	1515
150	170	?	20	1380
170	300	yellow stained lime-dolo chert steaks broken	130	1360
300	305	red clay seam	5	1230
305	385	broken chert-dolo	80	1225
385	670	lime-dolo gray	285	1145
670	975	gray & white lime-dolo-chert streaks	305	860
975	1035	dark brown & gray lime-dolo	60	555
1035	1110	broken white gray lime dolo-chert	75	495
1110	1155	dark & light gray lime-dolo	45	420
1155	1173	broken white & gray lime-chert	18	375
1173	1220	lime- dark yellow water stained	47	357
1220	1230	dark gray & white lime chert	10	310
1230	1335	lime dolo w/red clay steaks red water	105	300
1335	1460	dark gray lime-chert-dolo	125	195
1460	1510	broken lime-dolo gray & white	50	70
1510	1547	white sandstone	37	20
1547	1860	light gray lime	313	-17
1860	1880	dark gray dolo	20	-330

Table 6. Well construction report rock cutting samples description by depth for HI 5.

Depth in Feet				
From	To	Description	Thickness ft.	Elevation of unit top in ft.
0	125	light-dark gray lime chert	125	1110
125	150	light-dark gray lime chert black shale	25	985
150	305	light-dark gray lime chert	155	960
305	306	red water	1	805
306	560	light-dark gray lime chert	254	804
560	570	white sand lime light dark gray lime chert	10	550
570	600	light-dark gray lime-chert	30	540
600	620	white sand	20	510
620	680	light-dark gray lime chert	60	490
680	700	white sand	20	430
700	720	light-dark gray lime dolomite chert	20	410
720	722	void-broken	2	390
722	1055	light-dark gray lime dolomite chert	333	388
1055	1150	white sand, lime boulders	95	55
1150	1184	unknown	34	-40

Table 7. Well construction report rock cutting samples description by depth for HI 6.

Depth in Feet				
From	To	Description	Thickness Ft.	Elevation of unit top in ft.
0	40	gray limestone trace weathered chert	40	1160
40	45	gray lime chert traeces green-blue shale	5	1120
45	685	light-dark gray lime-chert	640	1115
685	765	dark-light gray lime chert white sand	80	475
765	815	light-dark gray lime-chert	50	395
815	830	white sand dark-light gray lime chert	15	345
830	840	light-dark gray lime-chert	10	330
840	885	light-dark gray lime-chert white sand green shale	45	320
885	930	light-dark gray lime chert weathered lime red stain	45	275
930	975	light brown pink gray lime chert weathered	45	230
975	995	light-dark gray dolomite	20	185
995	1000	gray weathered lime red clay red water	5	165
1000	1050	light brown pink lime-gray lime calcite weathered red water	50	160
1050	1195	dark gray dolomite red water	145	110
1195	1235	white sandstone	40	-35
1235	1255	dark gray dolomite	20	-75

Evaluation of the well data in Tables 5, 6, and 7 may indicate some correlation might be possible between the wells. The Gunter Sandstone can be identified as a white sandstone unit in all three wells and is verified by identification in the strip log. The presence of paleo karst can also be inferred by descriptions listed as “lime dolo w/red clay streaks red water”, “weathered lime red stain”, or “void-broken”. In all the well logs there are paleo karst indicators in the range of 300 feet in elevation. Karstic descriptions are interspersed throughout all of the well logs and are indicators of episodic uplift and subsequent weathering of the formations. The interspersed and uneven weathering creates difficulty with further stratigraphic classification.

If the assumption is made that geologic units are fairly continuous across the Holiday Island area then the HI 7 strip log information presented in Table 4 can be utilized to determine the geologic formation likely present at the base of the well borings. Likely geologic formation present at the base of the well is given in Table 8; note that HI 3 and HI 6 are not included due to a lack of location and thus elevation data. There are no major topographic features indicative of faulting such as lineaments between HI 7and HI 4 thus it is very likely that the formations are parallel between these wells. It should be noted that information in MacDonald (1977) and Pugh (2008) indicate that the aquifer formation at the base of the Holiday Island wells as being Gunter, Gasconade, or Roubidoux which according the extrapolation of the strip log information would be incorrect. Thus the Eminence Formation may be contributing more to the overall aquifer characteristics than previously thought. Lumping the Holiday Island wells in with others may not be giving an accurate picture of characteristics for the Gunter, Gasconade, or Roubidoux portions of the aquifer system.

Table 8. Formational information for Holiday Island Wells assuming formations are relatively flat and no major faulting with offset occurs between the wells.

Well ID	Depth of Well ft.	Elevation of wellhead ft.	Elevation of bottom of borehole ft.	Formation
HI 1	1063	1010	-53	Eminence
HI 2	1128	1100	-28	Eminence
HI 4	1880	1530	-350	Potosi
HI 5	1184	1110	-74	Eminence
HI 7	1800	1490	-310	Potosi

Graphs of pump test data for wells HI 1 and HI 4 taken from the Northern Arkansas Groundwater Inventory report (MacDonald 1977) are included as figures 4 and 5 respectively. Raw pump test data were interpolated from Figures 4 and 5 for input into the Aquifer Test computer program. A summary of results from Aquifer Test are presented in the methodologies section of this thesis and the full results are in Appendix B.

Figure 4. Pump test graph from Groundwater Inventory report (MacDonald 1977) for well HI 1. The data from these curves can be entered into Aquifer Test to derive K and S

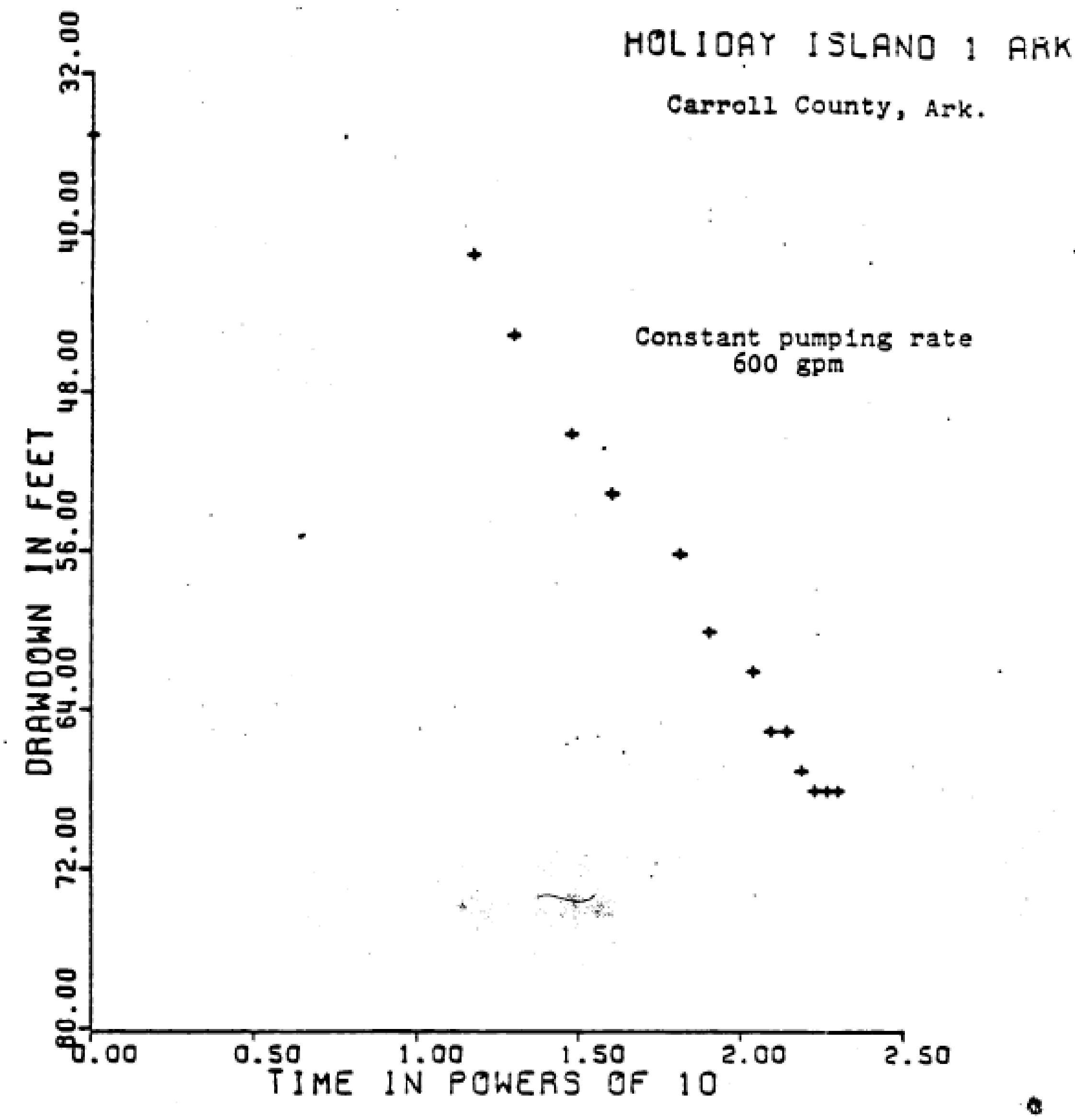
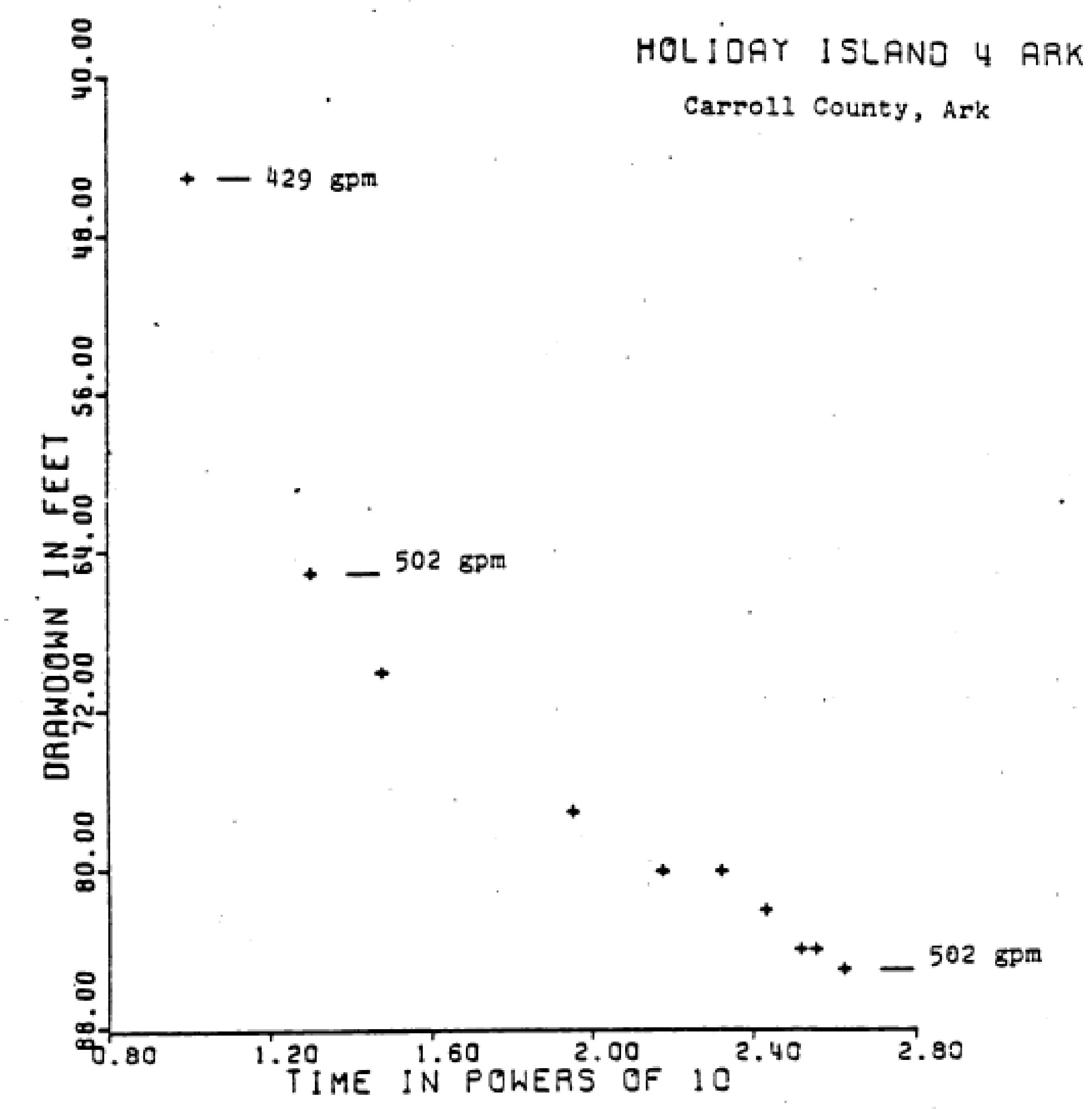


Figure 5. Pump test graph from Groundwater Inventory report (MacDonald 1977) for well HI 4.



C. CALICO ROCK WATER SYSTEM

The City of Calico Rock installed their first well in 1935 and additional wells in 1964, 1982, 1984, and 1998 (Cordova, 1992 and 2000, Taylor 2013). There are well construction reports available for the wells drilled in 1984 and 1998 with an additional record of a well that was drilled in 1999 but had to be abandoned due to a static water level of three feet. Copies of the construction reports are included in Appendix A. Well depths range from 125 feet to 2,134 feet and well yields are between 40 and 170 gallons per minute. Well casing and grouting vary from the unknown up to 680 feet. Hydrology in the Calico Rock area is also influenced by proximity to the White River.

Wellhead protection areas for the Calico Rock wells were determined in 1992 and 2000 by the ADH as reported in two reports titled *Wellhead Protection Program Phase 1: Delineation of the Wellhead Protection Area for Calico Rock* by Bob Cordova. The second report done in 2000 was completed to develop a wellhead protection area for an additional well drilled in 1998. Due to the unknown construction details of well 1 and relatively shallow casing depths for wells 2 and 4 in Calico Rock it was determined by the ADH that the wells were under the direct influence of surface water (GWUDI) (Cordova 1992 & 2000). Since the determination was made that the wells are directly influenced by surface water, the wellhead protection area included the entire surface watershed above well 1 which also included the watersheds for wells 2 and 4. The Theis nonequilibrium formula was utilized to determine a radius for protection of wells 5 and 6. The calculated protected area for well 5 fell within the watershed protection area for well 1. Well 6 had a protection radius of 3,100 feet due to the higher pump rate of the well.

Cordova (1992) indicates there are two wells with nomenclature 3a and 3b, drilled in 1970 and 3/1/1982 respectively. The well referenced as 3a is not included in subsequent ADH reports and for the purposes of this thesis is ignored due to a lack of information regarding this well. The well referenced as 3b is listed as well 4 in subsequent ADH reports and the name CR 4 is used to reference this well in this thesis. Well 4 as defined by Cordova (1992) is renamed well 5 in subsequent reports and the name CR 5 is used for this well in this thesis.

Selected data for the Calico Rock wells are in Table 9 and the driller's log of rock information for wells CR 4, CR 5, and CR 6 are located in Tables 10, 11, and 12, respectively. A strip log completed for well CR 6 follows as Figure 6 with a summarized table of rock formation information as Table 13. There are no well construction reports available for Calico Rock wells CR 1 and CR 2 which were installed in 1935 and 1964, respectively. Well construction reports for wells CR 4, CR 5, and CR 6 are located in Appendix A along with a report for a well that had to be abandoned due to a high water table.

Table 9. Well construction information for Calico Rock Wells. Well yield is listed as a range when available reports from different times give various data.

Well ID	Depth ft.	Completion Date	Depth to Water Level ft.	Casing Diameter in.	Casing Depth ft.	Grout Depth ft.	Elevation	Well Yield
CR 1	150	1/1/1935	unknown	unknown	10	Unknown	340	150
CR 2	125	1/1/1964	unknown	6	28	Unknown	460	50
CR 3	63	3/16/1999	3	6	n/a	n/a		n/a
CR 4	650	3/1/1982	unknown	6	80	80	490	37-40
CR 5	1729	2/14/1984	70	6	540	540	540	50-56
CR 6	2200	9/15/1998	314	10	680	680	760	150-170

Table 10. Well construction report rock cutting samples description by depth for CR 4.

Depth in Feet				
From	To	Description	Thickness ft.	Elevation of unit top in ft.
0	80	dirt and sandrock	80	490
80	650	limestone	570	410

Table 11. Well construction report rock cutting samples description by depth for CR 5.

Depth in Feet				
From	To	Description	Thickness ft.	Elevation of unit top in ft.
0	16	overburden	16	540
16	25	St. Joe lime	9	524
25	70	Everton Sand	45	515
70	71	Opening	1	470
71	100	Everton Sand	29	469
100	1390	Dolomite	1290	440
1390	1640	Roubidoux	250	-850
1640	1729	Limetsone	89	-1100

Table 12. Well construction report rock cutting samples description by depth for CR 6.

Depth in Feet				
From	To	Description	Thickness ft.	Elevation of unit top in ft.
0	62	overburden	62	760
62	118	gray limestone	56	698
118	139	gray limestone	21	642
139	241	dark gray and light gray limestone	102	621
241	278	dark gray limestone	37	519
278	282	broken gray limestone	4	482
282	386	gray limestone	104	478
386	414	dark gray and light gray limestone	28	374
414	529	dark gray limestone	115	346
529	586	dark gray and dark brown dolomite	57	231
586	588	broken gray dolomite with chert	2	174
588	590	gray limestone	2	172
590	596	broken gray limestone low volume water	6	170
596	700	gray dolomite with chert	104	164
700	780	dark brown dolomite	80	60
780	1080	dark gray and light gray dolomite with chert more water	300	-20
1080	1370	dark gray dolomite with chert more water	290	-320
1370	1460	light gray dolomite with chert more water	90	-610
1460	1610	gray dolomite with sandstone more water	150	-700
1610	1890	light gray dolomite with chert and sandstone	280	-850
1890	1960	light and medium gray dolomite with chert	70	-1130
1960	2080	dark gray dolomite with chert more water	120	-1200
2080	2134	gray dolomite with chert and sandstone more water	54	-1320
2134	2200	total depth	66	-1374

Figure 6. Strip log generated from well cuttings from CR 6 well construction provided by William Prior of Arkansas Geological Survey.

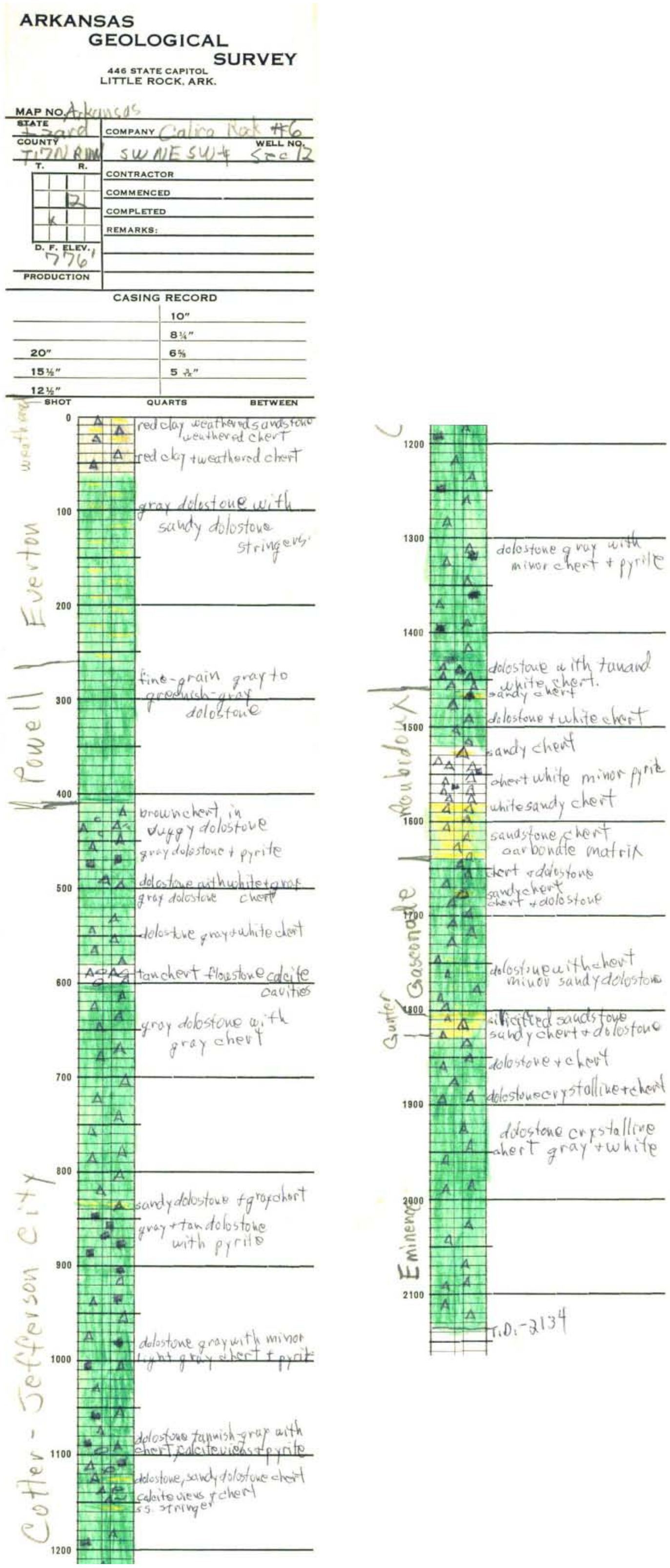


Table 13. Well strip log information for CR 6 from William Prior of Arkansas Geological Survey.

Depth in Feet					
From	To	Thickness ft.	Formation	Elevation at top of formation ft.	Elevation at base of formation ft.
0	260	260	Everton	760	500
260	410	150	Powell	500	350
410	1460	1050	Cotter/Jefferson City	350	-700
1460	1640	180	Roubidoux	-700	-880
1640	1800	160	Gasconade	-880	-1040
1800	1830	30	Gunter	-1040	-1070
1830	2200	304	Eminence	-1070	-1440

A comparison between Table 12 and Table 13 for well CR 6 indicates that the driller's construction log of cutting descriptions could not be used to determine geologic formations. Descriptions from the driller do not correlate to any formational changes listed in the strip log. Construction logs from wells CR 4 and CR 5 lack any detailed information regarding rock composition. It should be noted that the construction record for well CR 5 does document a one foot opening which indicates karst. The opening would have been cased and grouted when the well was completed.

Table 14 was generated utilizing the information in Table 13 to determine geologic formations likely present at the base of the well. This is assuming there is relative formational continuity over the Calico Rock area. Unlike the Holiday Island wells the Calico Rock wells have a large variation in well yield and overall it is significantly less than the Holiday Island wells. CR 1 well produces 150 GPM even though it is only 150 feet deep. Because only the first 10 feet of the borehole is cased, groundwater closer to the surface could augment the well's yield. This also would indicate that near surface karst or fracturing likely increases well productivity.

Table 14. Formational information for Calico Rock wells assuming formations are relatively flat and no major faulting with offset occurs between the wells.

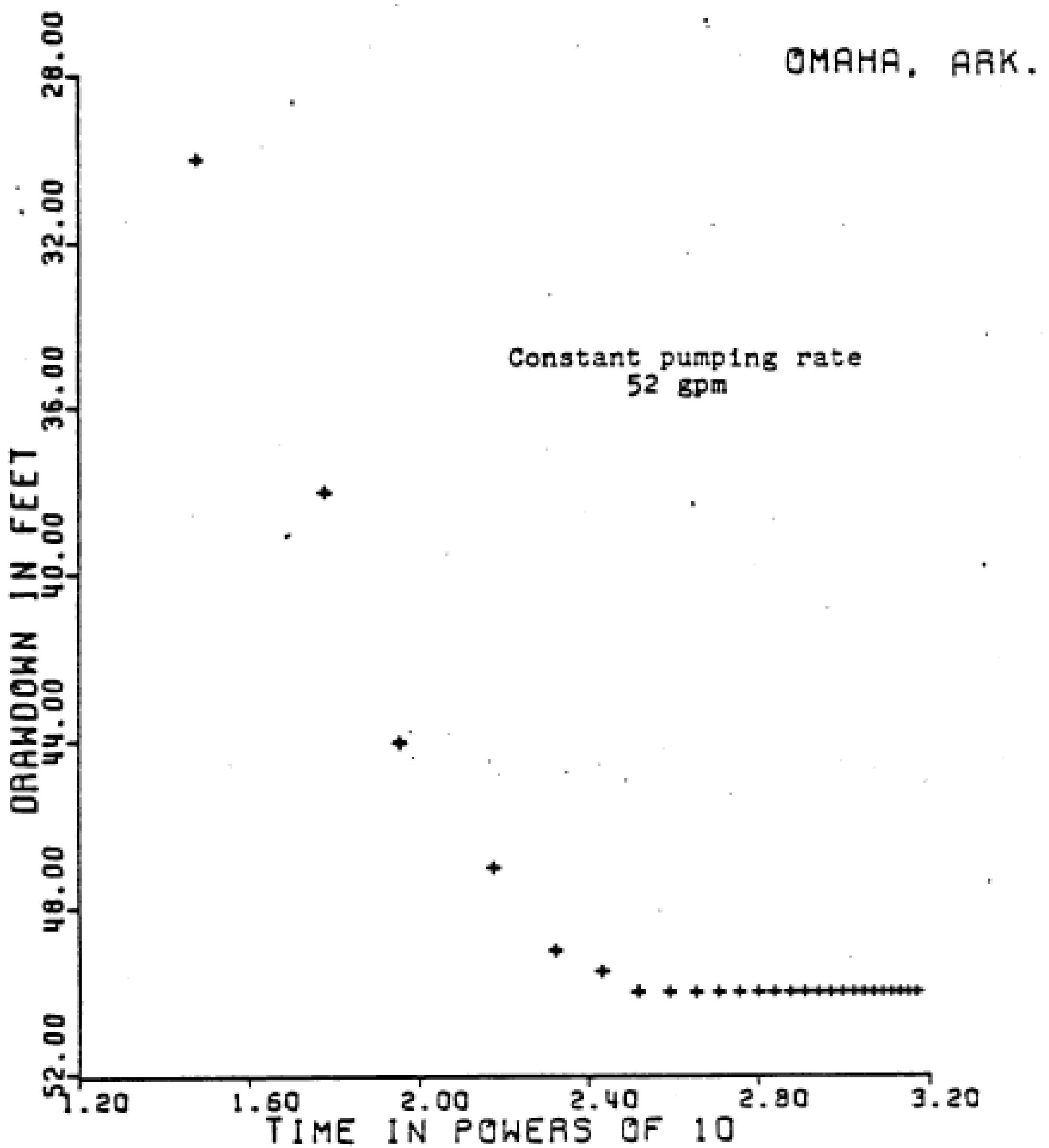
Well ID	Depth of Well ft.	Casing Depth ft.	Elevation of wellhead ft.	Elevation of bottom of borehole ft.	Formation at bottom of well boring	Yield GPM
CR 1	150	10	340	190	Cotter/Jefferson City	150
CR 2	125	28	460	335	Powell	50
CR 4	650	80	490	-160	Cotter/Jefferson City	37
CR 5	1729	540	540	-1189	Eminence	50-56
CR 6	2200	680	760	-1440	Eminence	150-170

It is likely that in the Calico Rock area karst and fracture flow is limited to the near surface. The difference in elevation between CR 1 and CR 2 is 120 feet which is significant since their overall well depths are 150 and 125 feet. However the yield for CR 2 of 50 gpm which has only 97 feet of open borehole is comparable to the yield of CR 1 of 150 gpm which has 140 feet of open borehole. These yields when compared to the other deeper wells indicate that significant groundwater flow is occurring at shallow depth below land surface, <150 feet and that the hydraulic conductivity of the aquifer decreases with increasing depth. When water production of the deeper wells in the Calico Rock area are compared with the water production of CR 1 and CR 2, it could be inferred that the hydraulic conductivity of CR 1 and CR 2 are tied to more significant near surface weathering of rock formations.

The deeper wells with deeper casing in Calico Rock have relatively lower yields for the length of open borehole compared to the two shallow wells. Construction report logs for CR 5 and CR 6 contain no indications of karst, paleo karst, or fracture features at elevations below 469 feet. This would indicate tighter formations with less karst or fracture flow. CR 6 yields more water than CR 5 because it is deeper and has a larger boring diameter of 10 inches. The Holiday Island wells have indicators of paleo karst at the lowest elevation of -35 feet with more frequent indicators throughout the well borings. The deeper Calico Rock wells also reach much lower elevations even though these wells penetrate the same geologic formations as the Holiday Island wells. This may indicate that since they are at lower elevations they have had less opportunity through geologic time to be subjected to uplift and subsequent karstic weathering. Since Calico Rock is at the fringe of the Springfield plateau there may also be less faulting and fracturing.

A graph of a pump test for a well in Omaha, Arkansas documented in the Northern Arkansas Groundwater Inventory report (MacDonald 1977) is included as Figure 7. After studying water well information in the report it was determined that the well in Omaha, Arkansas had similar hydrologic properties. Raw pump test data were interpolated from Figure 7 for input into the Aquifer Test computer program. A summary of results from Aquifer Test are presented in the methodologies section of this thesis and the full results are included in Appendix B.

Figure 7. Pump test graph from Groundwater Inventory report (MacDonald 1977) for well in Omaha, Arkansas.



III. METHODOLOGY

The computer modeling program available for usage for completion of this study is Visual Modflow flex. With the exception of certain test runs, Modflow 2005 from SWS numerical engine was utilized to generate results. The strongly implicit procedure numerical solver was used in the Modflow 2005 package. A PEST Single Run and Conjugate Gradient Solver were utilized in the modeling program. Multiple models were generated for each well utilizing pumping time lengths of 1 day, 30 days, 90 days, 180 days, 1 year, and 5 years.

A. VERIFICATION OF PREVIOUS WORK

Initially, the work reported by Cordova, in various "Phase 1: Delineation of the Wellhead Protection Area" ADH reports, was duplicated. Calculations that were completed utilizing Theis methods found in Fetter 1994, while incorporating some rounding and estimations, do match results reported by Cordova. However, the hydrogeologic values Cordova utilized for the wellhead protection area calculations could be improved upon by using more accurate or appropriate data. More appropriate data can be found in various reports which contain results from individual pump tests on specific wells in this study. Values Cordova utilized for input into the Theis nonequlibrium formula are included Table 15. Wells CR 1, CR 2, and CR 4 were determined by Cordova to be impacted by surface water. Therefore, the entire watershed around these wells became the wellhead protection area and as a result Theis calculations were not completed for these wells. Note that for the purposes of this thesis the following abbreviations are used: K for hydraulic conductivity, T for transmissivity, SC for specific capactiy, S for storatitivity, S_y for specific yield, and S_s for specific storage.

Table 15. Hydrologic values Cordova utilized and his calculated results for the wells from both Holiday Island and Calico Rock sites.

Well ID	Aquifer Thickness ft.	Discharge ft^3/day	time days	T ft^2/day	S	Drawdown Assumption ft.	WHPA radius result ft.
HI 1	235	77000	0.125	500	0.0001	1	2000
HI 2	235	96250	0.17	500	0.0001	1	2500
HI 4	237	96250	0.17	500	0.0001	1	2500
HI 5	200	96250	0.21	500	0.0001	1	2800
CR 5	250	7700	0.042	300	0.0001	0.1	1000
CR 6	300	32725	0.83	300	0.0001	2	3100

Improvement can be made by using values that have been determined for specific wells when they are available. Data from wells with similar hydrologic conditions can be utilized for wells that lack information. Also, a range of values can be modeled to determine the influence of different parameters.

B. DETERMINING HYDROLOGIC VALUES

Table 16 lists values calculated for three wells utilizing Aquifer Test and pump test graphs from MacDonald (1977). Multiple methods were completed utilizing Aquifer Test and the full results are included in Appendix B. The best fit was determined for each well and reported in Table 16. As previously noted wells in Calico Rock have not had pump tests performed. Therefore, the Omaha pump test information from MacDonald (1977) was utilized because it was the only well that had similar hydrologic values to the Calico Rock wells. It is interesting to note that the Moench Fracture Flow method was the best fit for the data from the Omaha well. Table 17 compiles available information taken from Pugh (2008) and MacDonald (1977) for wells in the study. The studies have a general lack of data regarding wells located in the Everton, Powell, and Cotter/Jefferson City Formations. There was only one well identified in the various reports that provided data for the Cotter Formation. Additionally, there is little data on the Eminence Formation which is at the base of the deeper wells. However, it was unknown at the time of the studies that the Holiday Island wells penetrated the Eminence Formation. The work completed by Prior on the strip logs is the only information available regarding the water wells in this study to scientifically determine rock formations present in the boreholes.

Table 16.   Data generated by taking information from Figures 4, 5, and 7, were input into Aquifer Test, for determination of a best fit of the resulting graphs for generation of new hydrogeologic values.

Well ID	T (ft^2/day)	K (ft/d)	S	Method
HI 1	2220	3.95	0.0093	Theis
HI 4	2100	1.53	0.0108	Newman
Omaha	198	1.58	0.0002	Moench Fracture Flow

Table 17. Hydrogeologic values from Pugh (2008) and MacDonald (1977).

Well ID	Yield gpm 1977	Draw-down ft. 1977 & 2008	SC gal/min/ft 1977 & 2008	T gpd/ft 1977	T ft^2/day 1977	T ft^2/day 2008	K ft/day 2008
HI 1	600	68	8.82	5866	784	2530	1.76
HI 2	500	60	8.33			3150	1.58
HI 4	502	85	5.91	10602	1417	1390	0.69

Pugh (2008) also compiled hydrologic values based on geologic formation. This compilation used the geologic formation at the base of the well for classification. It was noted in the report that additional geologic formations above the classified formation that were uncased could not be excluded from contributing to the overall hydraulic properties of the well. Also due to the difficulty classifying formations based on well cutting samples there may be inaccuracies associated with those designations. However, the data helps to build a picture of hydrologic values for the areas. Information from Pugh (2008) for pertinent formations has been listed in Table 18. Because there was only one well reported as being in the Cotter Formation there was not a mean value for K calculated. It should be noted that the Holiday Island wells which were used in the study were classified as being in the Gunter or Roubidoux Formations. This may indicate that other, high yielding, deep wells in the Ozark aquifer system may actually have significant production from deeper geologic formations. The additional report regarding HI 7 from the ADH indicates that HI 7 has a SC value of 3.6 gal/min/ft with 141 ft of drawdown at a pumping rate 520 gallons per minute. Converting 520 gallons per minute to cubic feet per day gives 100,100 cubic feet per day. Utilizing a Theis equation from Fetter (1994), transmissivity can be estimated to be 2733 ft^2/day for HI 7 which falls within the ranges for T for HI 1 and HI 2 as reported by Prior (2008).

Table 18. Hydrogeologic values from Pugh (2008) based on geologic formation.

Geologic Formation	Mean T ft^2/day	Maximum thickness ft.	Estimated K ft./day	Mean reported K ft./day
Cotter Dolomite	147	525	0.28	
Roubidoux Formation	983	455	2.16	1.49
Van Buren Formation	1290	600	2.15	0.44
Gunter Sandstone member of the Van Buren Formation	981	100	9.81	0.51
Potosi Dolomite	2150	390	5.51	0.85

All of the aforementioned hydrologic values for transmissivity, hydraulic conductivity, specific capacity, and storativity can be used to determine values appropriate for each water supply well in Holiday Island and Calico Rock. These values are estimates and give a range of values to input into the model. They can be utilized to determine initial appropriate values for specific storage and specific yield. The model was utilized to determine the most appropriate values through a trial and error process. This will ultimately provide calibrated, steady state results.

C. DETERMINING POTENTIOMETRIC SURFACE AND FLOW DIRCTIONS

Information regarding the potentiometric surface for all the wells in the two study areas was collected and is presented in Table 19. Only HI 1, HI 2, and CR 5 have data from more than one gauging event. The data indicates that there is large variability in the potentiometric surface over time. The range of depth to water level values listed in Table 19 for wells HI 1, HI 2, and CR 5 vary as much as 77 feet. Because the wells have been sampled at various times under various conditions with unknown pumping schedules the range in gauging data values are high. The fact that there is such variation through time does devalue the information and indicate that the data cannot be directly used to form an accurate potentiometric map. However, data for HI 4 and HI 5 could confirm that the potentiometric surface does parallel topography. In the case of HI 4 and HI 5, HI 4 is at a higher topographic elevation and does have a corresponding higher groundwater elevation than HI 5.

Table 19. Compiled available gauging data for Holiday Island and Calico Rock wells with elevations of nearby water bodies. WRHI stands for White River at Holiday Island and WRCR stands for White River at Calico Rock.

Well ID	Construction Date	Water Level At Construction ft.	Water Level 1977 Report	Water Level 2004 Report	Water Level 2008 Report	Water table or river elevation ft.	Range ft.
HI 1	12/15/1970	60	100	42	86	968-910	58
HI 2	12/18/1970	60			136	1040-964	76
HI 4	6/15/1972	520	520			1010	
HI 5	6/23/1977	146				964	
WRHI						900	
CR 5	2/14/1984	70		40		500-470	30
CR 6	9/15/1998	314				446	
WRCR						320	

Measured water table information regarding Calico Rock wells CR 5 and CR 6 do not confirm that topography affects the potentiometric surface when the water table elevations are compared with topography. This is probably due to several factors. The Calico Rock wells were measured 14 years apart, they do not have as much vertical separation topographically, and they are separated hydrologically by a small valley. There are no gauging data available for wells CR 1, CR 2, or CR 4. In order to develop aquifer head information for the model, an estimate of water table elevation must be made for these wells. For the purposes of this thesis it was assumed that the reported level of the bottom of the casing is equal to the initial water table elevation at construction.

The best information regarding the potentiometric surface for the two study areas comes from Schrader (2004). Since the data reported in Schrader (2004) utilized many wells that were gauged in a short time span, it is the best available estimation of groundwater flow in the Ozark aquifer. The constant head values necessary for building a MODFLOW model were partially based on the potentiometric map presented in Schrader (2004). Applicable portions of the map can be seen in Figure 8 for Holiday Island wells and Figure 9 for Calico Rock wells. Other factors to be considered in determining groundwater flow directions include the proximity and potential influence of surface water bodies and topography.

Figure 8. Portion of potentiometric surface map from Schrader (2004). HI 1 well has elevation listed at 968 feet at the top of the figure. Study of the figure indicates a gradient of approximately 10 feet per mile (0.0019) for wells HI 2, HI 4, and HI 5.

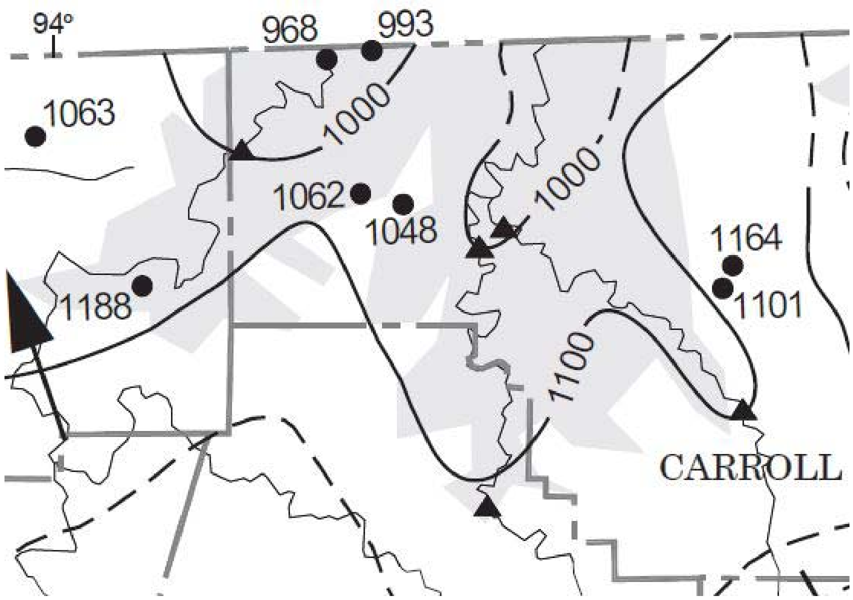
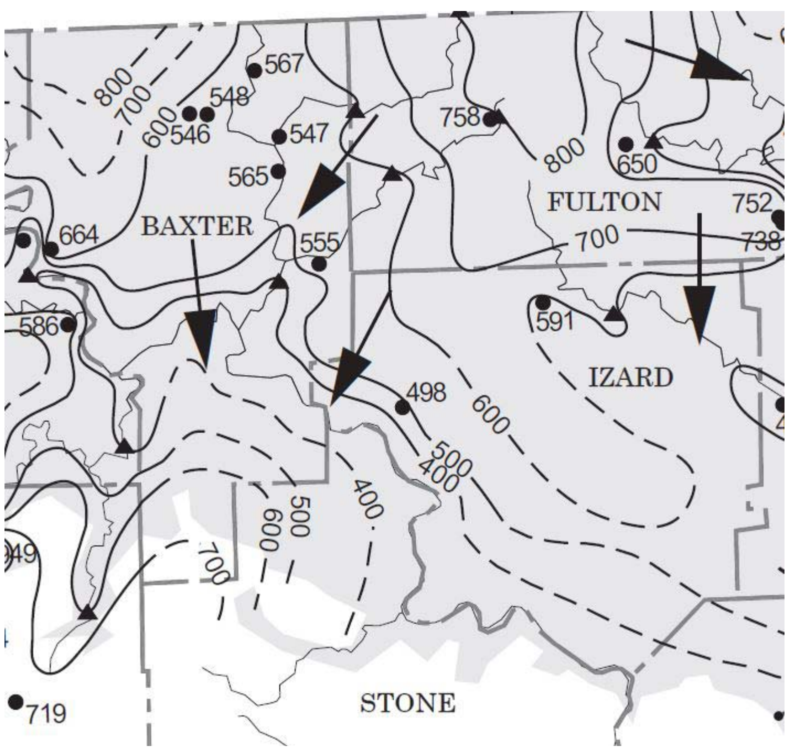


Figure 9. Portion of potentiometric surface map from Schrader (2004). CR 5 well has elevation listed as 498 near the center of the figure. Study of the figure indicates a gradient of approximately 50 feet per mile (0.0095) for CR 4, CR 5, and CR 6.



It should be noted that the gradients of groundwater flow are quite different between the two study areas. There is a much steeper overall gradient in the Calico Rock area and the gradient appears to steepen somewhat as groundwater approaches the White River. In the Holiday Island area the gradient does not appear to increase as steeply as it approaches the river and it is less steep overall. However, the gradient information for Calico Rock must be tempered with the observation that there were no wells gauged south or west in the down gradient direction from the Calico Rock area. Therefore, flow directions and gradient are an estimate.

The Holiday Island wells are all deeply cased and thus are primarily affected by regional aquifer flow with the exception of HI 1. From a study of the surface streams, the potentiometric map, and the White River a general flow direction from the southeast to the northwest is established for HI 2, HI 4, and HI 5. Well HI 1 is unique in that it is on an island and surrounded by the waters of Table Rock Lake and the White River. Flow direction for the aquifer around HI 1 was from the topographic high of the island to the lake. A gradient of 0.0355 ft/ft was calculated based on the water level elevation change between HI 1 and the elevation of the White River.

Calico Rock wells CR 5 and CR 6 are similar in construction to the Holiday Island wells. These wells both have casing depths greater than 500 feet and are probably influenced only by the regional aquifer flow. This flow was assumed to be in the general southwest direction perpendicular to the general trend of the White River in the area. Wells CR 1, CR 2, and CR 4 each have unique characteristics.

Well CR 1 is in close proximity to Spring Creek and its confluence with the White River. Considering the relatively high yield and shallow casing depth of CR 1 it is likely that there is hydrologic connection of the well with surface water. Flow direction for CR 1 is from the northeast. A gradient of 0.0135 ft/ft was calculated for CR 1 based on distance from the White River and an assumed water table elevation of 10 feet below land surface for the well and a downgradient water level equal to the approximate elevation of the White River.

CR 2 is similar to CR 1 in construction with a shallow casing depth but it is located further away and higher in elevation from the White River. The nearby stream is intermittent with a smaller watershed. Flow direction for CR 2 is assumed to be from the topographically higher land east of the well down to the river which is southwest. A gradient of 0.0329 ft/ft was calculated for CR 2 based on distance from the White River and an assumed water table elevation of 28 feet below land surface for the well.

Well CR 4 is also located nearby an intermittent stream. However, since the well is cased to 80 feet and well yield is relatively low at 37 gpm it is less likely to be influenced by the stream. Flow direction for CR 4 is from the northeast which is topographically higher and toward the drainage basin in the southwest.

D. DETERMINING RECHARGE VALUES

Humans have become more acutely aware of how the Earth's climate changes around them and how this can influence people on a local scale. Drought could impact the viability of both municipal well systems. Therefore it is pertinent to model the systems at a steady state and also determine what influence variations in precipitation might have on the viability of the wells. Yearly precipitation averages are listed in Table 20. An aquifer recharge rate of 15% of the yearly precipitation is listed in Table 20. These values provide initial modeling recharge values, however, typical recharge values for the Ozark aquifer are sometimes quite low and modeling may require significantly smaller recharge inputs in order to reach a calibrated steady state. Evapotranspiration values were not added to the model in order to simplify modeling parameters.

Steady state and transient models were developed. Then recharge rates were varied in the models to simulate variations in precipitation. This tests the sensitivity of the model with respect to recharge.

Table 20. Average total yearly precipitation from NOAA, 2014

Location	Average Yearly Precipitation in.	15% of Average Precipitation in.	50% of Average Recharge in.
Holiday Island	46.9	7.0	3.5
Calico Rock	47.8	7.2	3.6

E. DETERMINING PHYSICAL FRAMEWORK OF MODELS

The physical framework for the models is highly dependent upon the limitations of the MODFLOW Flex program. The user manual for the program indicates that an unlimited number of cells and large grid size is feasible when running the program on appropriate computer hardware. This was found, through trials of many, many test runs, to be inaccurate and impractical. With the computer system, hardware, and set up available for completion of this study, the maximum grid size that could be reasonably processed is 250 cells by 250 cells. This was established by doing many trial runs on the well HI 2. The limitation on grid size affected how the models were developed. Given the distance between the wells in each study area it became impossible to model multiple wells in the same model on a scale that would develop appropriate results.

1. AQUIFER THICKNESS

The deeper wells of Holiday Island and Calico Rock have open boreholes spanning many formations in the Ozark aquifer. As was previously discussed, it is not possible based on the available data to determine individual sections and their corresponding detailed hydrologic information. Given the information contained in the boring logs and published formational descriptions it is very likely that there are rock layers which behave as aquitards and others act under fracture flow or karstic conditions and the aquifers might also have artesianal properties. A great variety of hydrologic properties can be deducted from any one well construction log. Primary water flow into the well bores may be through discrete zones with very high hydraulic conductivity values. However, aquifer tests that have been completed on wells in this study have not been done in a way that can assign specific hydrologic values to individual aquifer formations. Thus it is necessary to make assumptions and use average values to be able to develop a model based on what is known. Sensitivity analysis were completed on one well to determine the effect of various aquifer thicknesses on modeling results.

As it is truly unknown what portions of each well bore section are acting as aquifers; it is prudent to assume that the aquifer thickness correlates to the height of the water table. This may not necessarily be true in actuality, especially where the water table level is above the well casing. Aquifer thickness was assumed to be equal to the distance from the bottom of the borehole to the top of the water table in all wells except CR 2. Elevations had to be adjusted in order to eliminate negative elevations because MODFLOW cannot process negative elevations. Well CR 2 required thickness to be added to the aquifer since a model area large enough to include the White River as a downgradient boundary was necessary. If thickness was not added to the CR 2 aquifer the White River elevation would have been negative. Elevation of the bottom of the well bore for all wells, except CR 2, was set at zero. Overall aquifer thickness for CR 2 was set at 300 ft. and the bottom of the borehole was set at 100 ft. with a river elevation of 85 feet.

2. HEAD BOUNDARIES

Models for HI 2, HI 4, HI 5, CR 4, CR 5, and CR 6 utilized constant head boundaries located upgradient and downgradient of the wells and were at elevations and locations appropriate for each well. Since it is best to simplify inputs and variables for modeling whenever possible; head boundaries were set on opposite sides of the model grid with the pumping well in the center of the grid for HI 2, HI 4, HI 5, CR 4, CR 5, and CR 6.

For HI 1 a constant head boundary was put in place running slightly east of north to slightly west of south on the topographic high of the island which is upgradient from the well. River boundaries were utilized to define the remaining area around the island.

For the model of CR 1 a stream boundary was added for Calico Creek and a river boundary for the White River. A constant head boundary was added upgradient from CR 1. Two modeling runs of CR 1 were completed with and without Calico Creek in the model. These results were then compared to determine the influence of Calico Creek on the aquifer.

The model for CR 2 was simplified to have a constant head boundary along one side of the model grid and a river boundary along the other side. This is appropriate given that the well is 3400 feet from the White River. After the river model was performed for time periods of one and five years, it was determined that there was no influence from the river on CR 2. Thus another model with a smaller grid size was completed.

Steady state models were developed initially without the influence of pumping wells. Aquifer values were adjusted in the steady state models until appropriate results were achieved. The resulting steady state head values were utilized in subsequent transient state model runs with the pumping well to provide initial head values. General head boundaries were tested in transient state model runs to determine any possible influence on results.

3. GRID DIMENSIONS

The HI 2 well was selected for experimentation and sensitivity analysis because it is fairly representative of all of the deeper cased wells in the two study areas. The well was modeled with multiple runs using various grid dimensions and grid sizes. Results of this analysis determined appropriate model dimensions for wells HI 4, HI 5, CR 4, CR 5, and CR 6. Grid dimensions for HI 1, CR 1, and CR 2 were based on surface water and topography features near the wells.

F. MODEL EXPERIMENTATION ON HI 2 WELL

Initially a variety of models were developed and calibrated to steady state. Then head values from the steady state runs were utilized in transient state model runs with a pumping well. Attempts were made to model two supply wells in the same model run. However, this became impractical because all the wells are too far apart to successfully model them together.

Attempts were made to utilize child grids in the modeling program which would allow grid refinement around the wellhead. Modeling experiments with child grids utilized the USGS MODFLOW-LGR from SWS solver. Results from child grid models were not substantially different enough from standard modeling methodology to warrant the additional work necessary for completing the child grids. Also, calibration of child grid models was problematic. Step down methods for grid refinement were considered, but due to time considerations it was not deemed feasible.

After initial modeling experimentation and testing it was determined to extensively model and test the well HI 2. This testing established modeling methodology that was effective for modeling wells HI 4, HI 5, CR 4, CR 5, and CR 6.

1. MODEL SOLVER AND PROGRAM INFORMATION

USGS MODFLOW 2005 from SWS was utilized as the solver in all subsequent models in this thesis. PEST Single Run was selected with LPF Property Package. The solver was the Conjugate Gradient Solver. Closure criterion was left at 0.01 for both head change and residual criterion.

Most of the figures generated by the modeling program had the style adjusted to display twelve contour lines and a 12 pt. Times New Roman font. Model results are listed as head values with two decimal points. Two decimal points is the default setting for MODFLOW and the ability to reduce value places was overlooked during modeling. Scientifically, the head values should have been rounded to the nearest foot and are rounded appropriately when reported in this thesis. Given time considerations it was impractical to remodel all the wells to adjust to the correct significant figures.

2. MODEL SIZE AND GRID SPACING

As was previously mentioned, multiple model test runs were made to determine the practical capabilities of the modeling program. This testing concluded that a 200 by 200 grid size was manageable by the program, while larger sizes caused the program to have excessive processing times and frequent errors.

Initially it was thought that a smaller grid size of 1,000 feet by 1,000 feet with grid sizes of 5 feet by 5 feet would be useful for determining what conditions were present close to the well bore for shorter modeling times. Then the model would be stepped up to larger scale models of 2,000 feet by 2,000 feet and 21,120 feet by 21,120 feet to determine influence for longer pumping time periods. The larger size was chosen in the hope that it would be large enough to exclude the interference created when drawdown from well pumping reaches the boundary of the model. This plan was enacted and the subsequent steps with results follow. Table 21 lists all input values for the experimental modeling of HI 2. Table 22 lists the results of this series of models as head elevations at the wellhead.

Table 21. List of values utilized in experimental modeling of well HI 2. Z Up stands for Upgradient Constant Head Boundary Elevation and Z Down stands for Downgradient Constant Head Boundary Elevation. Well bottom elevation remained constant at 0 feet and screen top elevation remained constant at 628 feet. Kz remained constant at 1E-5 ft./day, S_y was 0.2, and S_s was 1E-7 1/ft.

Model Run First number refers to model dimension in X and Y direction.	Model Size Feet	Cell Size Feet	K_x K_y ft./day	Recharge inches	Z Up Feet	Z Down Feet	Aquifer Thickness Feet	Wellhead Location x	Wellhead Location y	Pump Rate GPM
1000	1000	5	2	4	1038	1036	1037	500	500	-500
2000	2000	10	2	4	1039	1035	1037	1000	1000	-500
21120	21120	105.6	2	4	1057	1017	1037	10560	10560	-500
21120 Recalibrated	21120	105.6	3	0.25	1057	1017	1037	10560	10560	-500
4000 Calibrated	4000	20	3	0.25	1041	1033	1037	2000	2000	-500
21120 Recalibrated 1500 ft. Aquifer Thickness	21120	105.6	3	0.25	1057	1017	1500	10560	10560	-500
21120 Recalibrated 250 GPM	21120	105.6	3	0.25	1057	1017	1037	10560	10560	-250
21120 Recalibrated 628 ft. Aquifer Thickness	21120	105.6	3	0.25	1057	1017	628	10560	10560	-500
21120 Recalibrated 628 ft. Aquifer Thickness 250 GPM	21120	105.6	3	0.25	1057	1017	628	10560	10560	-250
4000 Calibrated 628 ft. Aquifer Thickness 500 GPM	4000	20	3	0.25	1041	1033	628	2000	2000	-500
4000 Calibrated 628 ft. Aquifer Thickness 250 GPM	4000	20	3	0.25	1041	1033	628	2000	2000	-250
105600 Feet Model	105600	528	3	0.25	1137	937	1037	52800	52800	-500

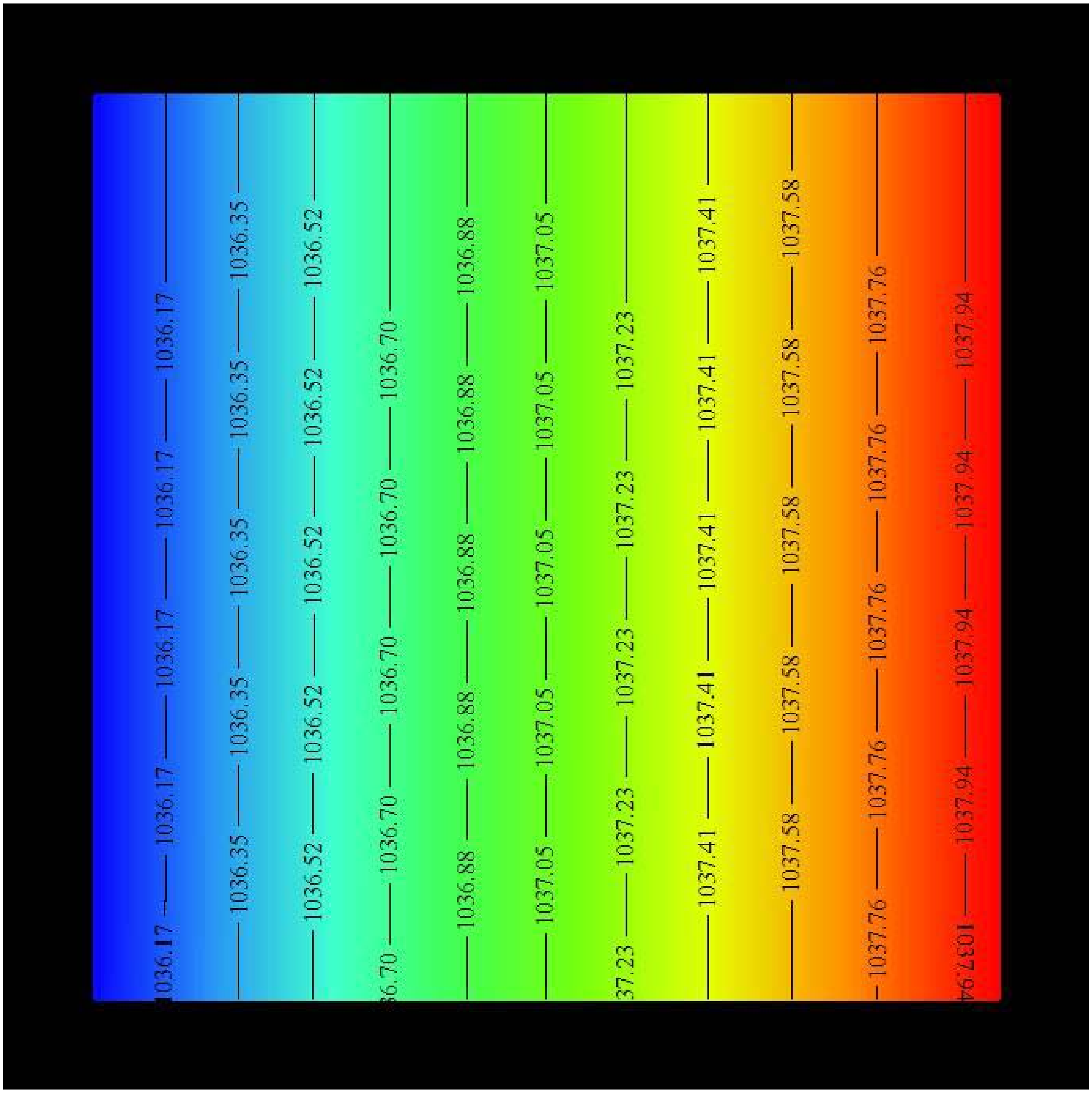
Table 22. Resulting head elevations at the wellhead for specified modeling times.

	Time in Days					
Model Dimension in X and Y direction and Run	1	30	90	180	365	1825
1000 Feet	999	980	950	905	812	0
2000 Feet	1005	991	984	973	950	772
4000 Feet Recalibrated	1018	1009	1005	1003	997	952
21120 Feet	1027	1027	1028	1032	1896	2883
21120 Feet Recalibrated	1004	1010	1012	1014	1018	1027

i. 1,000 FEET BY 1,000 FEET MODEL

A model was generated for a 1,000 feet by 1,000 feet area utilizing 200 by 200 cell modeling grid. This generated grid sizes of 5 feet per side. A variety of aquifer values were tested utilizing previously established data until a calibrated steady state was achieved. Values listed in Table 21 for the 1000 model run were determined to be appropriate for this model by the results of these initial steady state modeling runs. Figure 10 displays the result of the steady state model. Calibrated steady state head values resulting from this model were then utilized for input into a transient state model with the pumping well. Pumping time was varied to generate models for the time periods of 1 day, 30 days, 90 days, 180 days, 1 year, and 5 years. Results of this series of models are reported in Table 22.

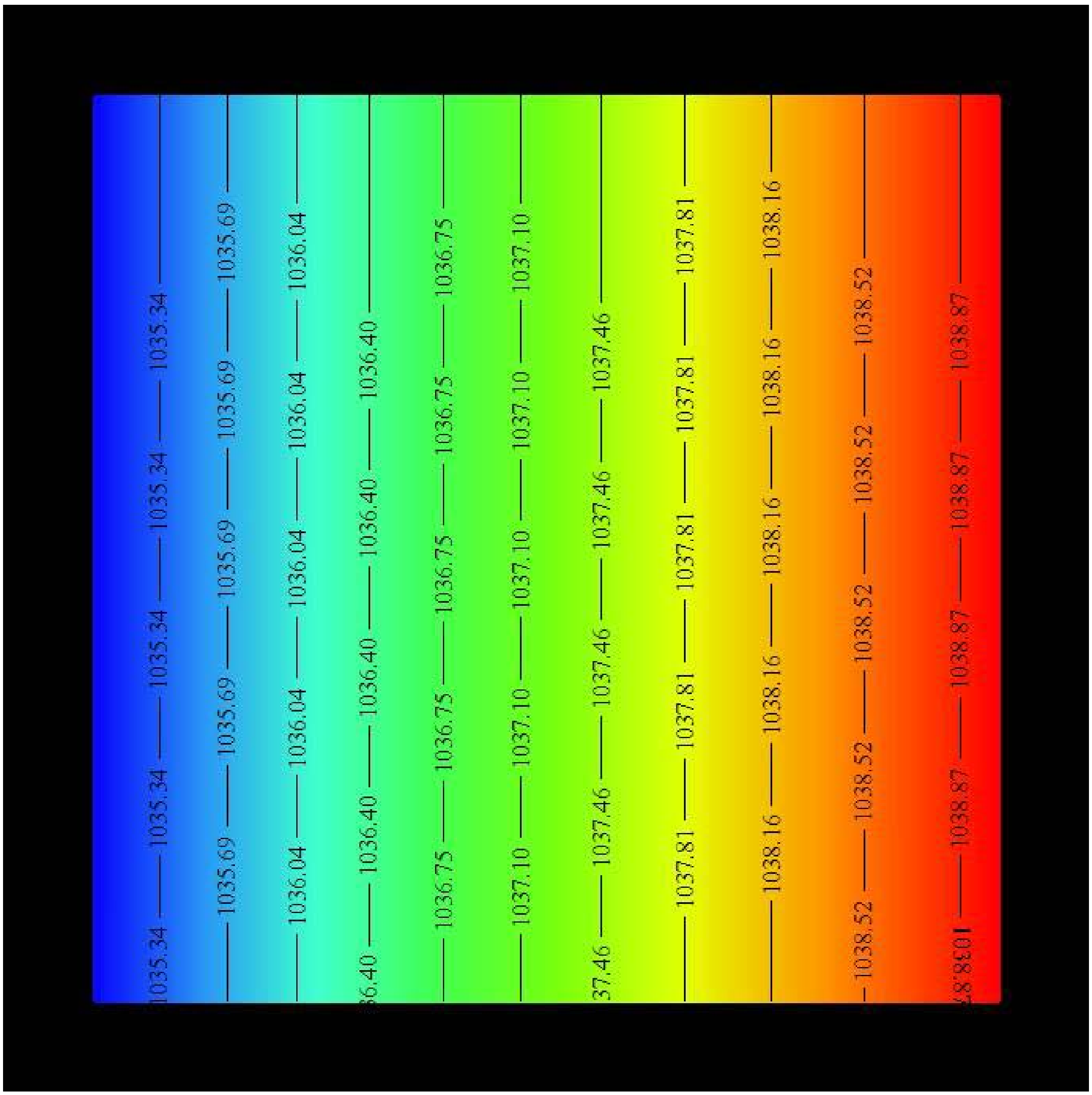
Figure 10. Results from 1,000 feet by 1,000 feet calibrated steady state modeling run.



ii. 2,000 FEET BY 2,000 FEET MODEL

Values derived from the calibrated steady state run for the 1,000 feet by 1,000 feet model were used for this model run. Model dimensions of 2,000 feet by 2,000 feet with 200 by 200 cells yielded a cell size of 10 feet by 10 feet. When these values were used for the model and a steady state run was generated the results of the model were not as well calibrated as for the 1,000 feet by 1,000 feet model. Results of the steady state run can be seen in Figure 11 and there is noticeable steepening of the head elevations in the downgradient direction. The enlargement of the individual grid dimension to 10 feet by 10 feet does create some loss of refinement at the wellhead.

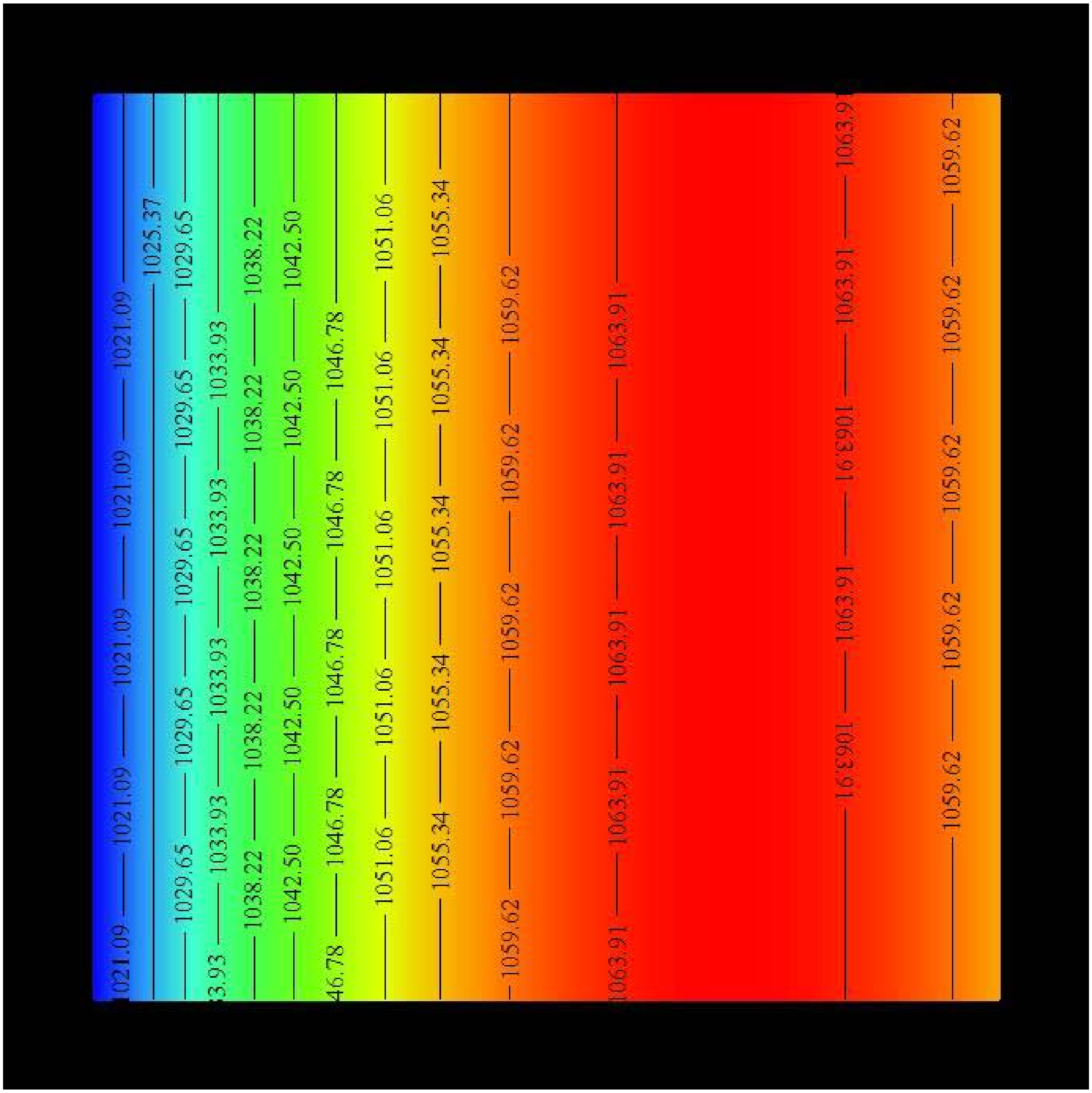
Figure 11. Results from 2,000 feet by 2,000 feet steady state model.



iii. 21,120 FEET BY 21,120 FEET MODEL

Aquifer values derived from the calibration of the 1,000 feet by 1,000 feet model were again used for this model run. A 21,120 feet by 21,120 feet grid with 200 by 200 cells results in a grid dimension of 105.6 feet by 105.6 feet. When these values were used for the model and a steady state run was generated the results of the model were not calibrated. Results of the steady state run using the aquifer values derived from the calibrated 1,000 feet by 1,000 feet run can be seen in Figure 12.

Figure 12. Results from the 21,120 feet by 21,120 feet steady state model.



There is intense steepening of the head elevations in the downgradient direction and an increase in head over the upgradient portion of the model. Comparing this information and the results from the 2,000 feet by 2,000 feet model results in the observation that proper calibration of the models cannot confidently occur when utilizing a small scale model. This is due to interactions with head boundaries and the model edges. Also, the recharge value utilized was excessive, resulting in a buildup of water table elevation. Transient state models with the pumping well were run utilizing the poorly calibrated steady state model. This enabled comparison to the results gained from the 1,000 and 2,000 feet runs using the same values. It should be noted that the head values increased across the model in the transient state run and that this effect was compounded as the modeling time increased. This invalidates all the results from the transient state runs for the improperly calibrated models but does provide important information regarding determining more appropriate values and techniques.

After studying the procedures and results of this first set of modeling experiments, it was decided to recalibrate the 21,120 feet model for comparison. It was also decided to try a 4,000 feet by 4,000 feet model utilizing the recalibrated aquifer values for further comparison and analysis.

iv. RECALIBRATED 21,120 FEET BY 21,120 FEET MODEL

Various values were again tested in a trial and error process to calibrate a steady state model. A 21,120 feet by 21,120 feet model size with 200 cells by 200 cells grid size resulted in cell dimensions of 105.6 feet by 105.6 feet. Values utilized to achieve the calibrated steady state are listed in Table 21 and the resulting head values from the model can be seen in Figure 13. Subsequent transient state runs utilized the calibrated head values from the steady state runs with various pumping times and the resulting well head water table elevations are listed in Table 22. Results from the one day, 90 days, and five year pumping time are included as Figures 14, 15, and 16 respectively.

Figure 13. Results from the recalibrated 21,120 feet by 21,120 feet steady state model.

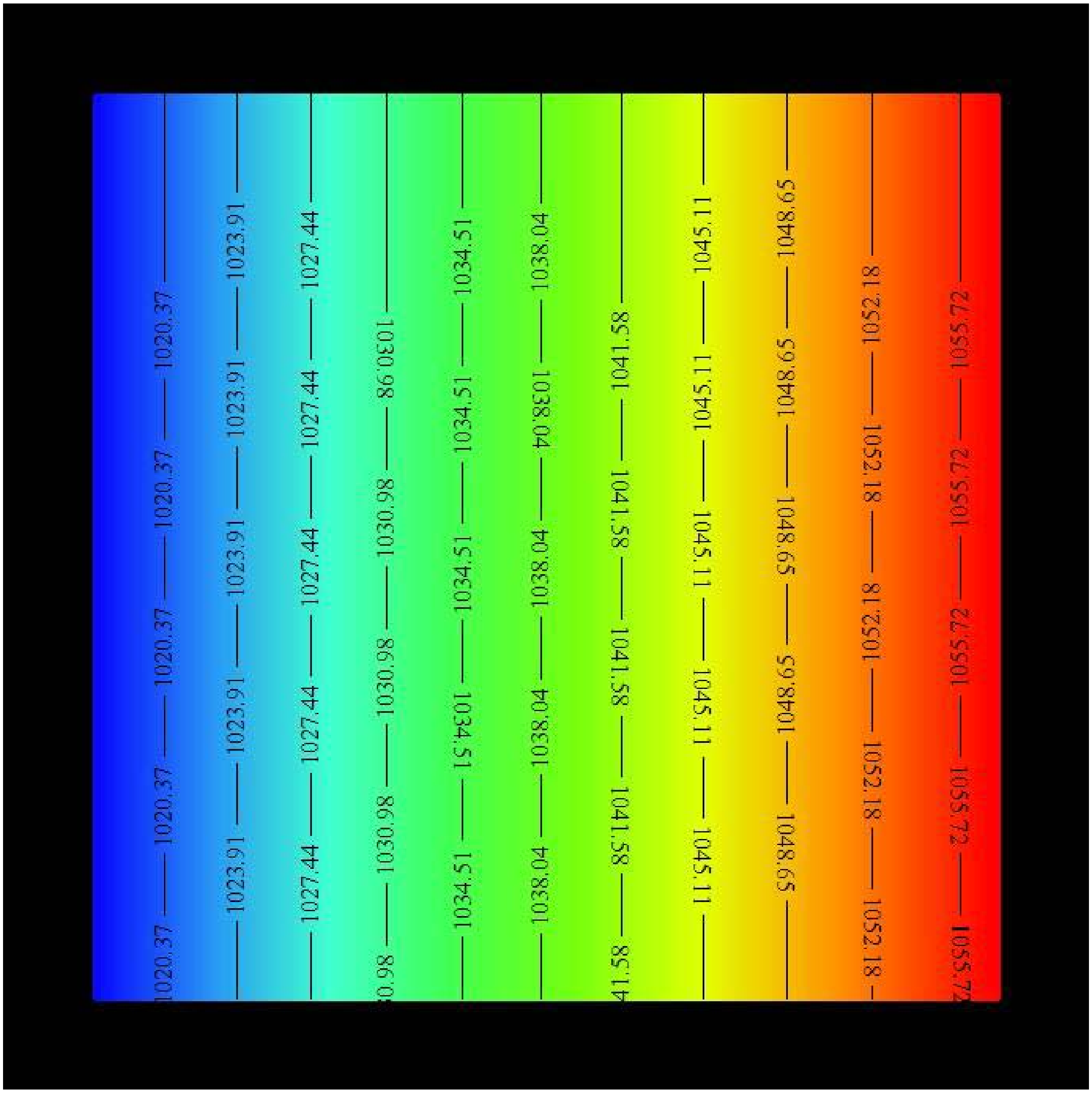


Figure 14. Result from transient state model run of one day of pumping for recalibrated 21,120 feet by 21,120 feet model.

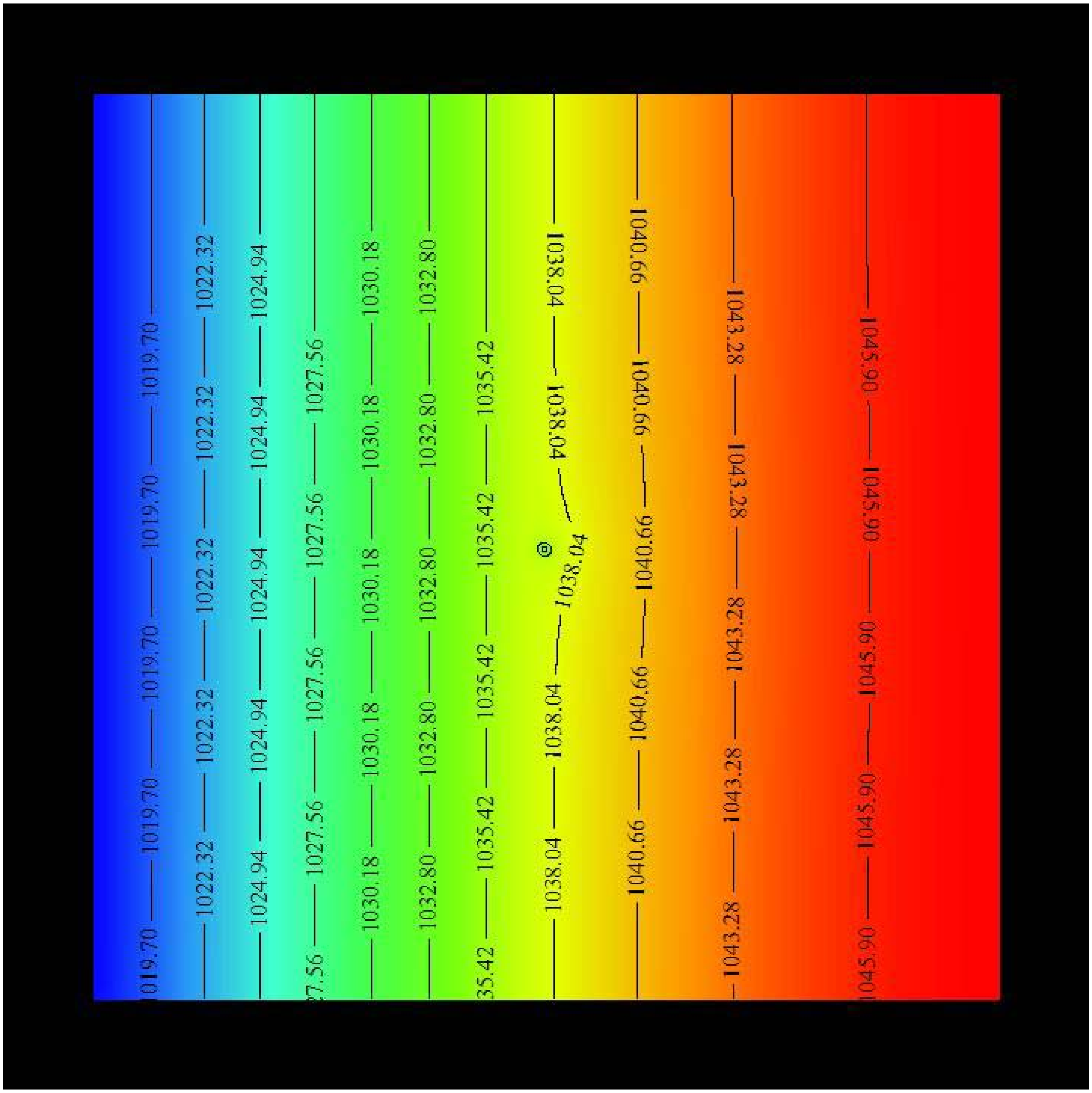


Figure 14 displays the effect that a large modeling area has on simulations with a short modeling run time. Due to a lager grid size the effect close to the well is unable to be modeled accurately. As one of the fundamental reasons for doing the modeling is to determine potential impact of contaminants near the wellhead in short time spans; the lack of accuracy is very problematic.

Figure 15. Result from transient state model run of 90 days of pumping for recalibrated 21,120 feet by 21,120 feet model.

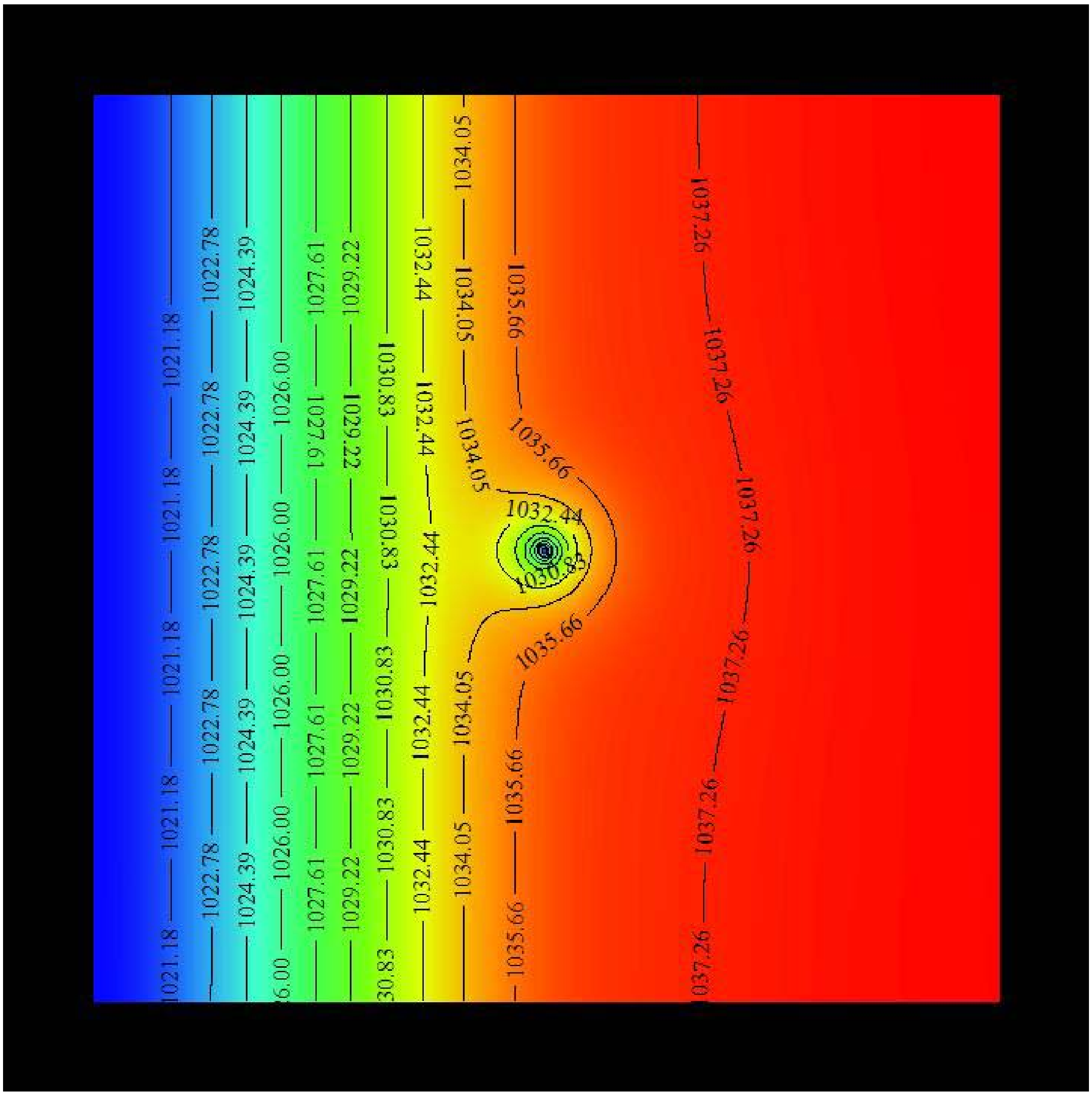


Figure 16. Result from transient state model run of five years of pumping for recalibrated 21,120 feet by 21,120 feet model.

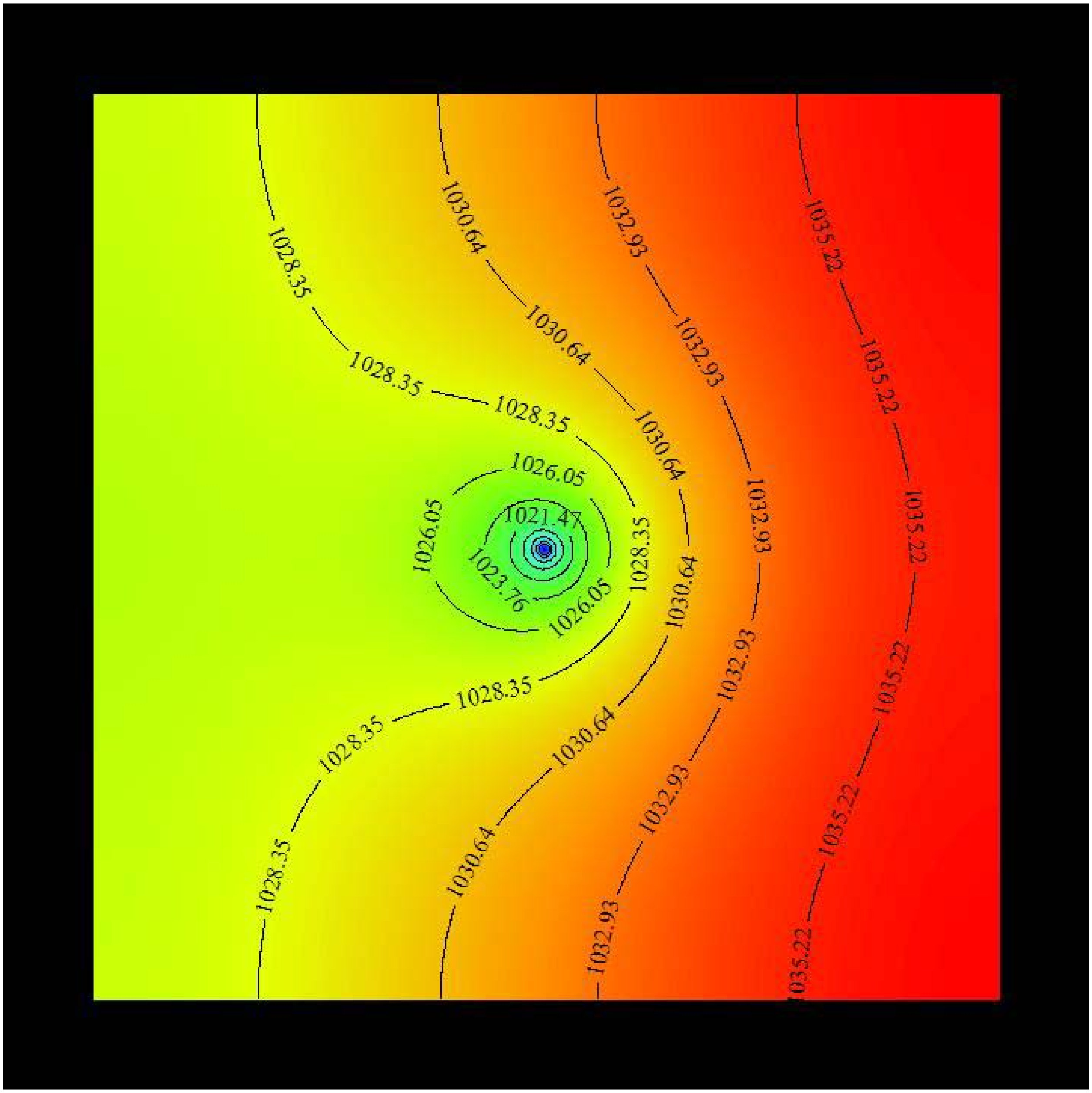


Figure 16 displays the effect that a large modeling area has on a longer modeling run time. It was hoped that by using a larger modeling area that interference with the boundary of the model could be avoided. However, this model result indicates that even with a modeling area of four miles by four miles the full extent of the influence created by the pumping well is still not displayed. After study of the results from this model run it was determined that a compromise in modeling size must be made. Since a modeling size of 1,000 feet by 1,000 feet resulted in poorly calibrated models and a size of 21,120 feet by 21,120 feet was unable to provide accurate result near the wellhead it was decided to try a 4,000 feet by 4,000 feet model size.

v. 4,000 FEET BY 4,000 FEET MODEL UTILIZING RECALIBRATED VALUES

Values derived in the recalibrated 21,120 feet by 21,120 feet model were utilized in the generation of a model with dimensions of 4,000 feet by 4,000 feet with 200 by 200 cells yielding a cell size of 20 feet by 20 feet. Values utilized to achieve the calibrated steady state are listed in Table 21 and the resulting head values from the model can be seen in Figure 17. Subsequent transient state runs utilized the calibrated head values from the steady state runs with various pumping times and the resulting well head water table elevations are listed in Table 22. Model results from the various pumping times are included as Figures 18 thru 23. Figure 24 displays the mass balance result from one day of pumping.

Figure 17. Results from the 4,000 feet by 4,000 feet steady state model.

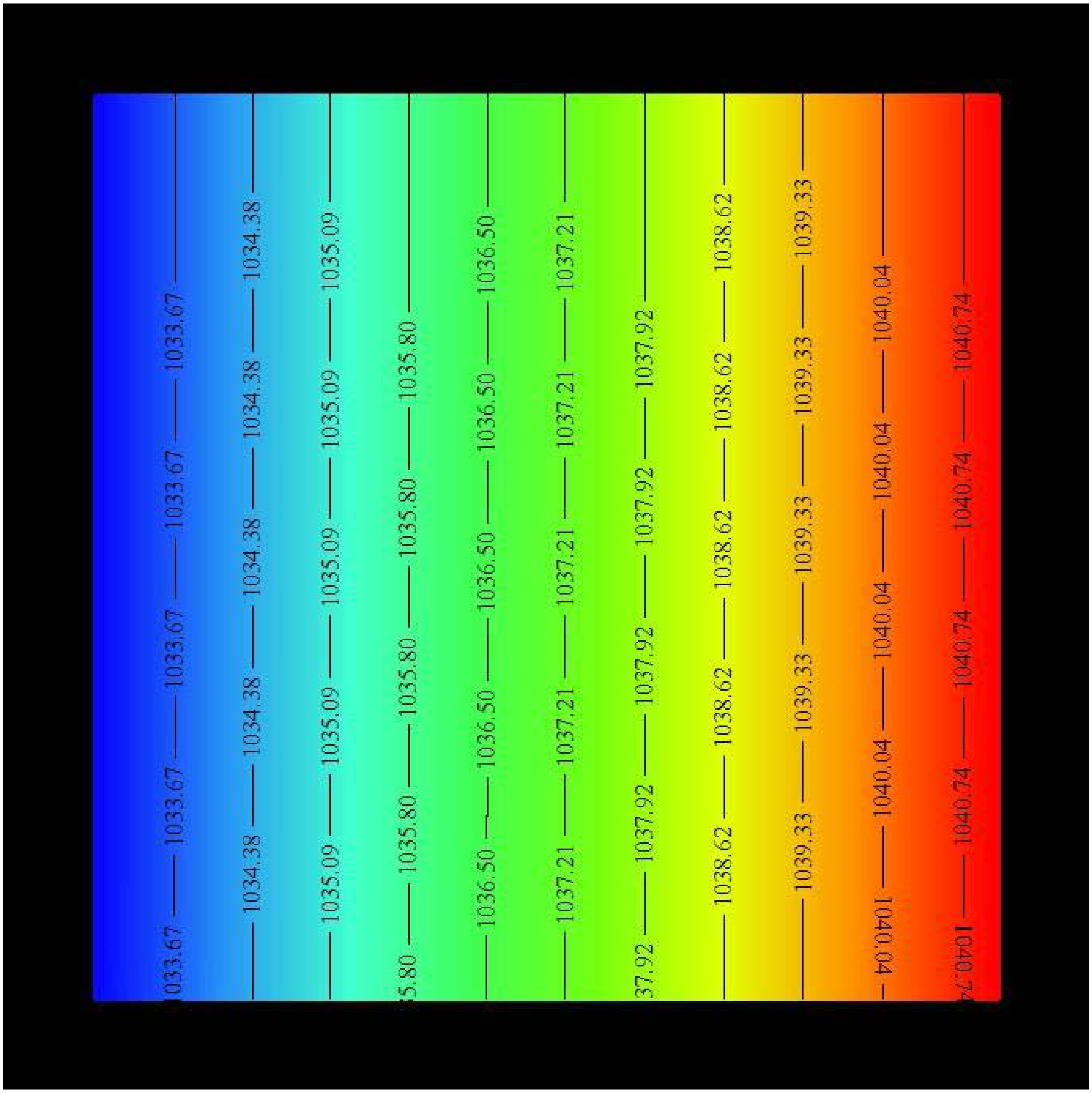


Figure 18. Result from transient state model run of one day of pumping for calibrated 4,000 feet by 4,000 feet model.

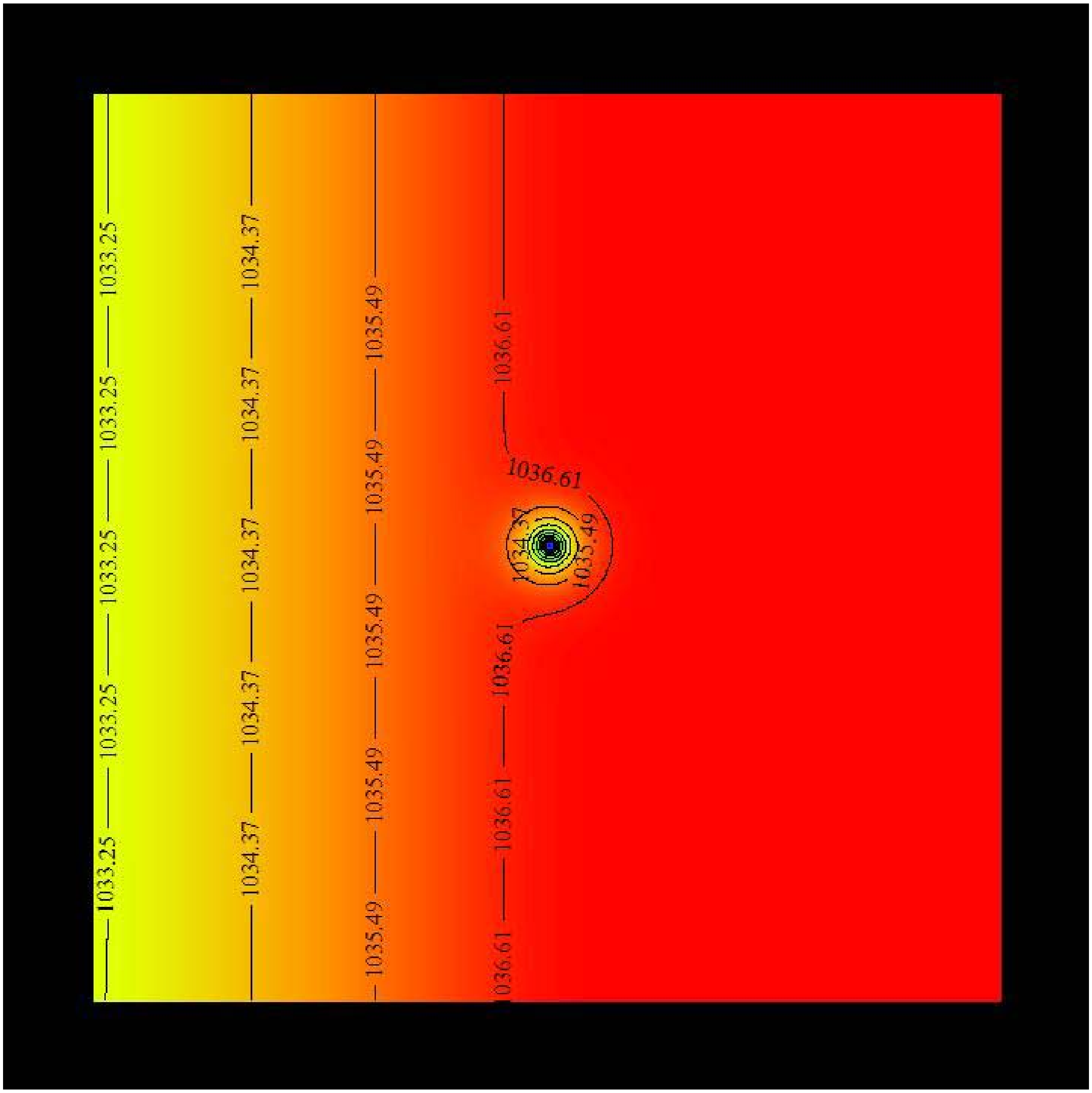


Figure 19. Result from transient state model run of 30 days of pumping for calibrated 4,000 feet by 4,000 feet model.

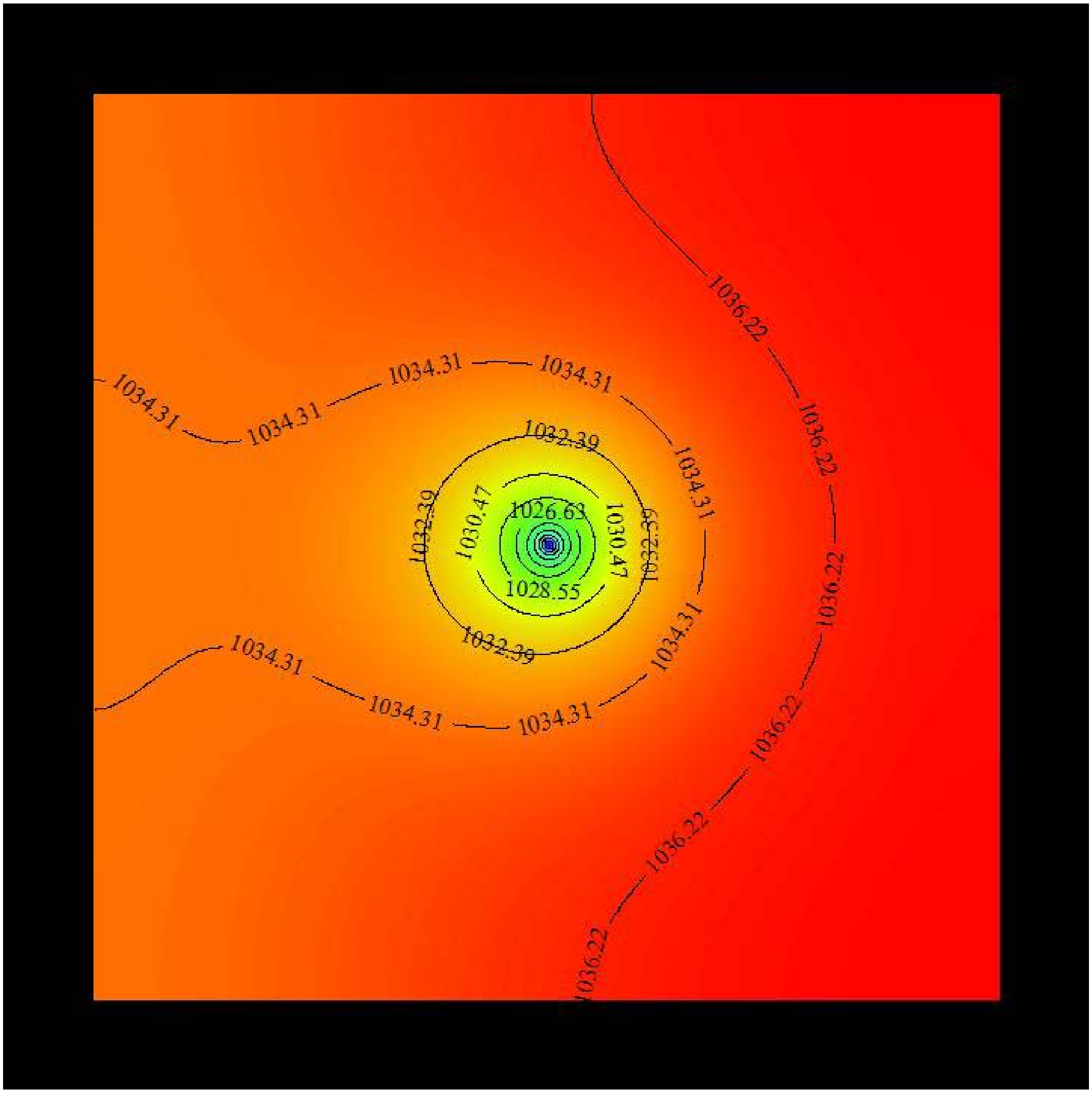


Figure 20. Result from transient state model run of 90 days of pumping for calibrated 4,000 feet by 4,000 feet model.

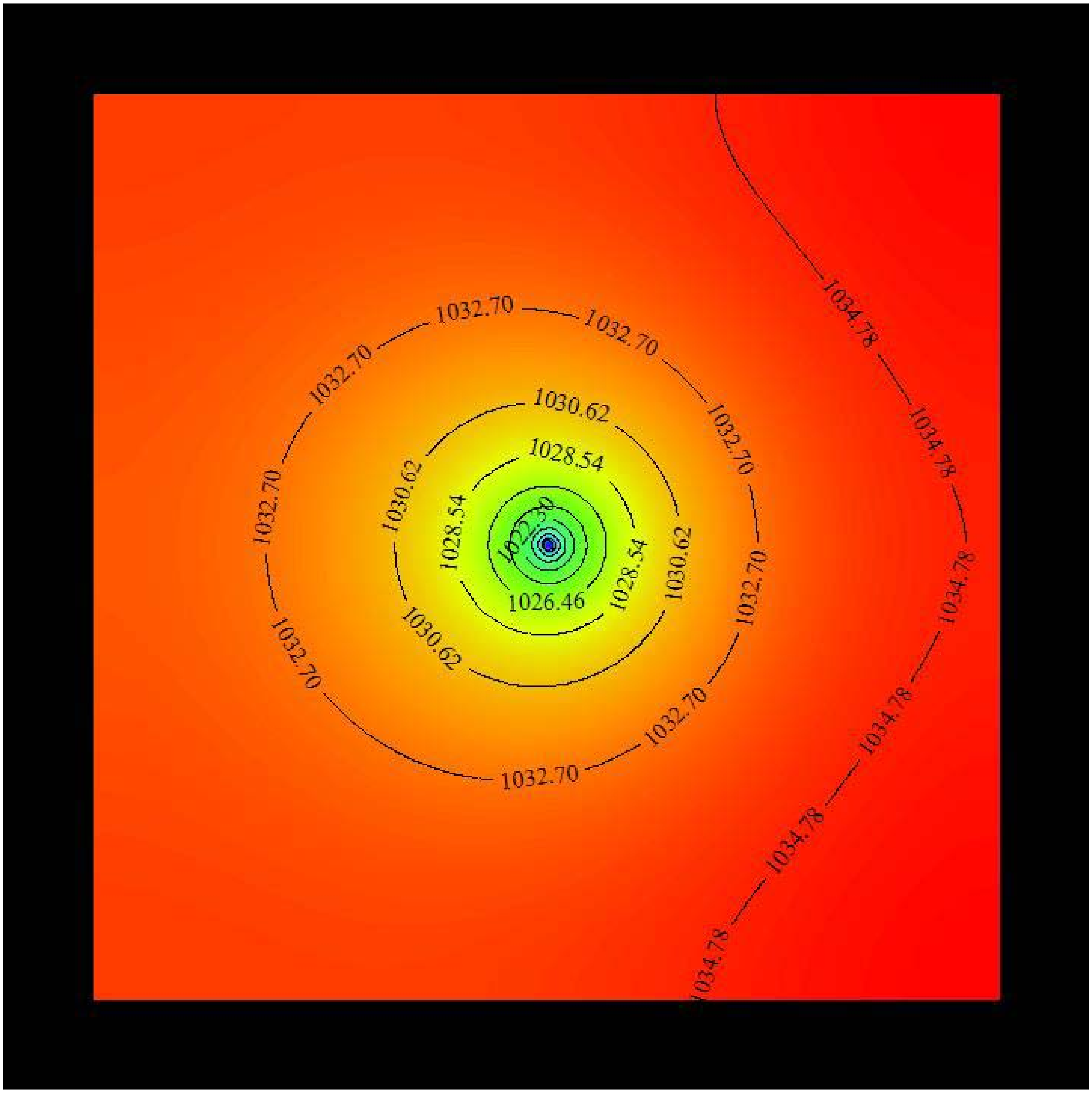


Figure 21. Result from transient state model run of 180 days of pumping for calibrated 4,000 feet by 4,000 feet model.

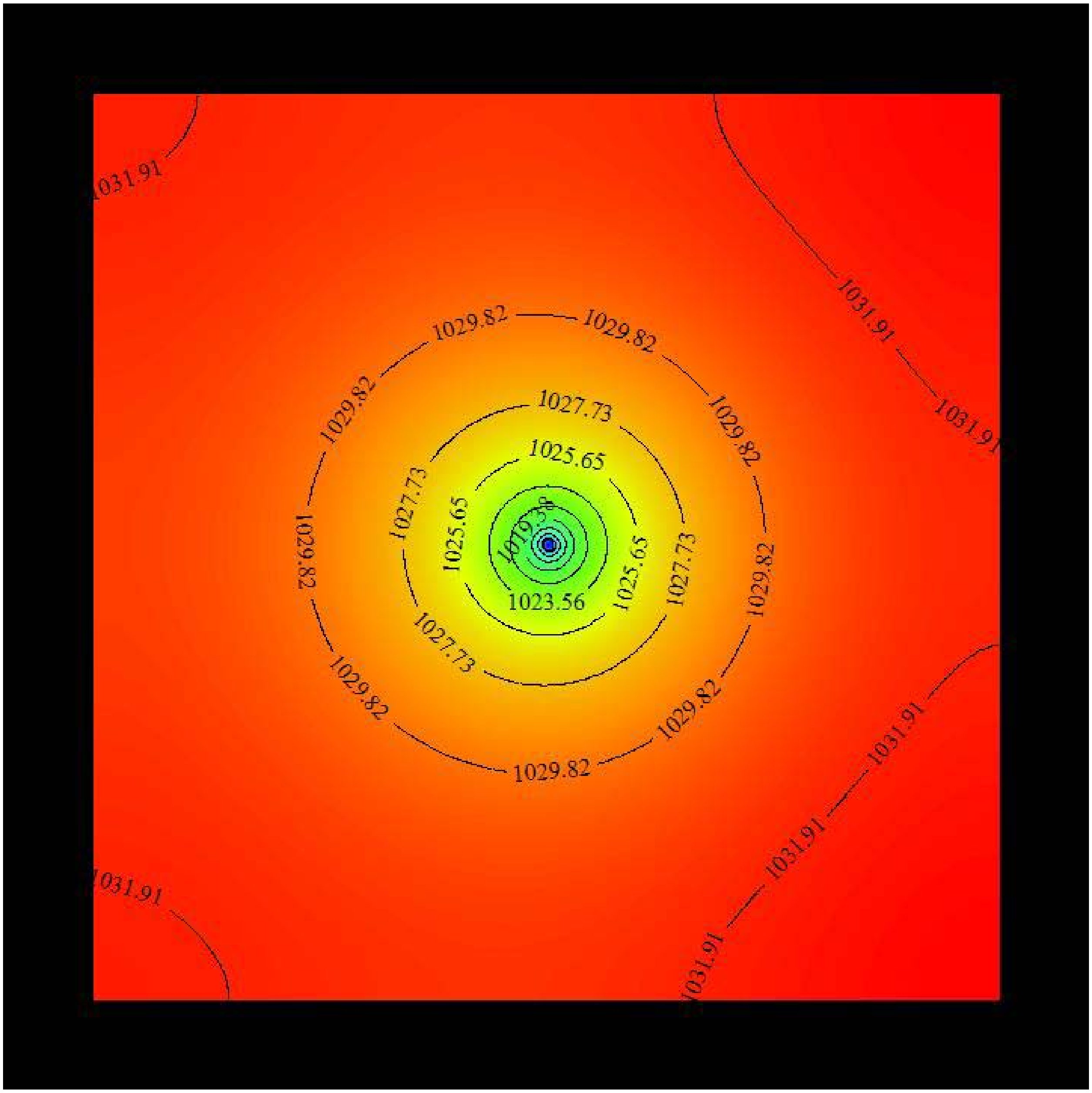


Figure 22. Result from transient state model run of one year of pumping for calibrated 4,000 feet by 4,000 feet model.

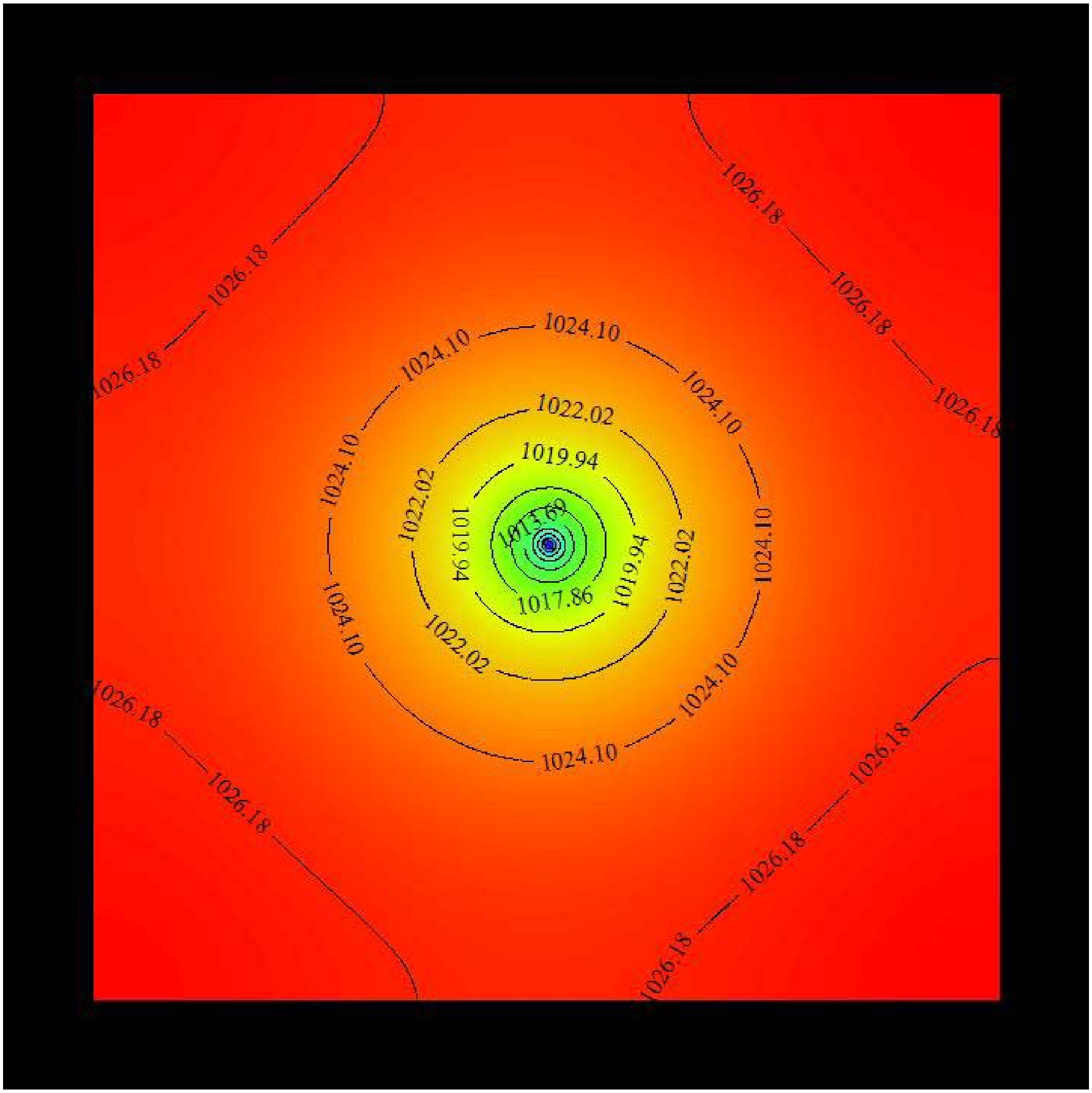


Figure 23. Result from transient state model run of five years of pumping for calibrated 4,000 feet by 4,000 feet model.

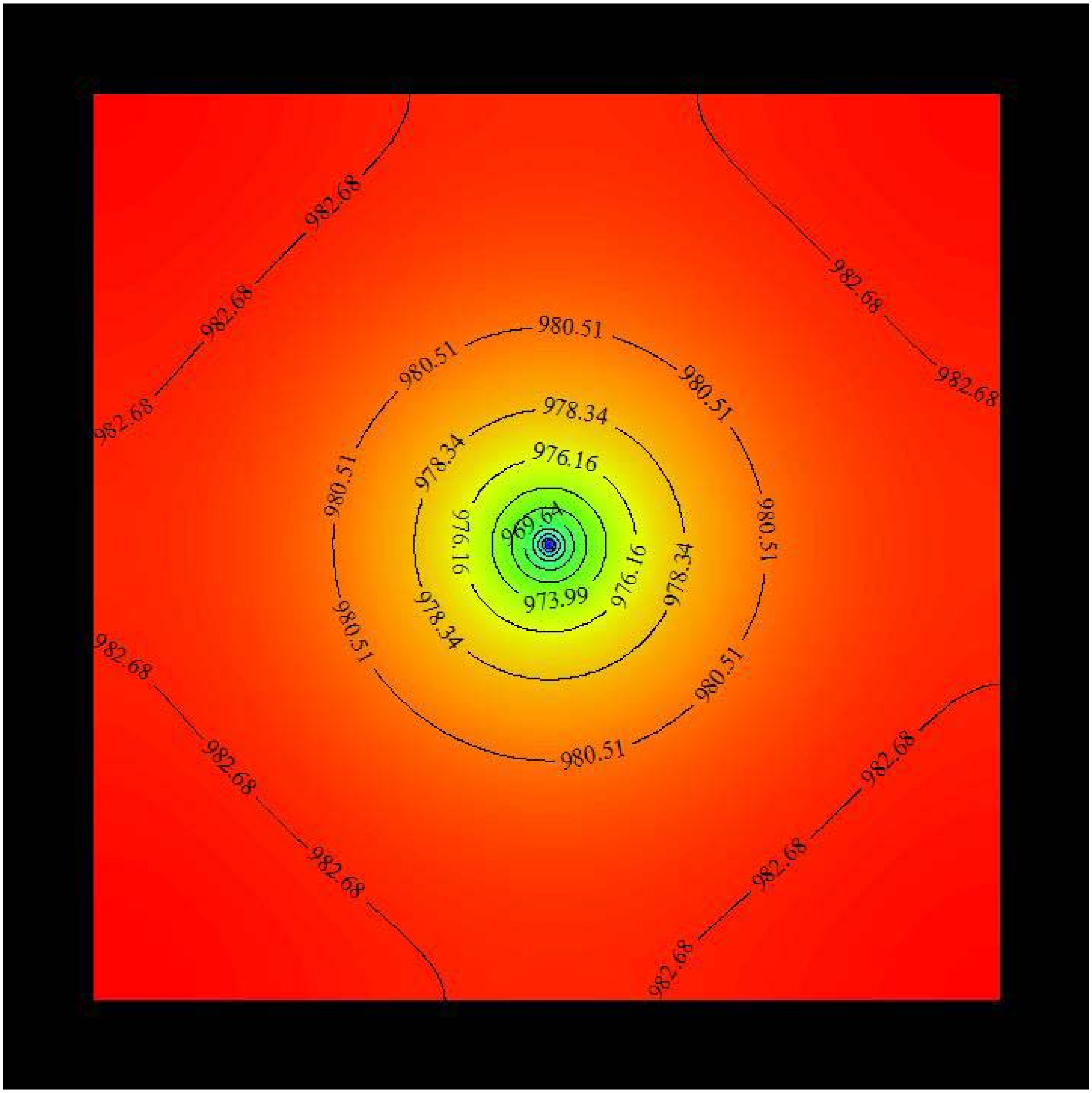
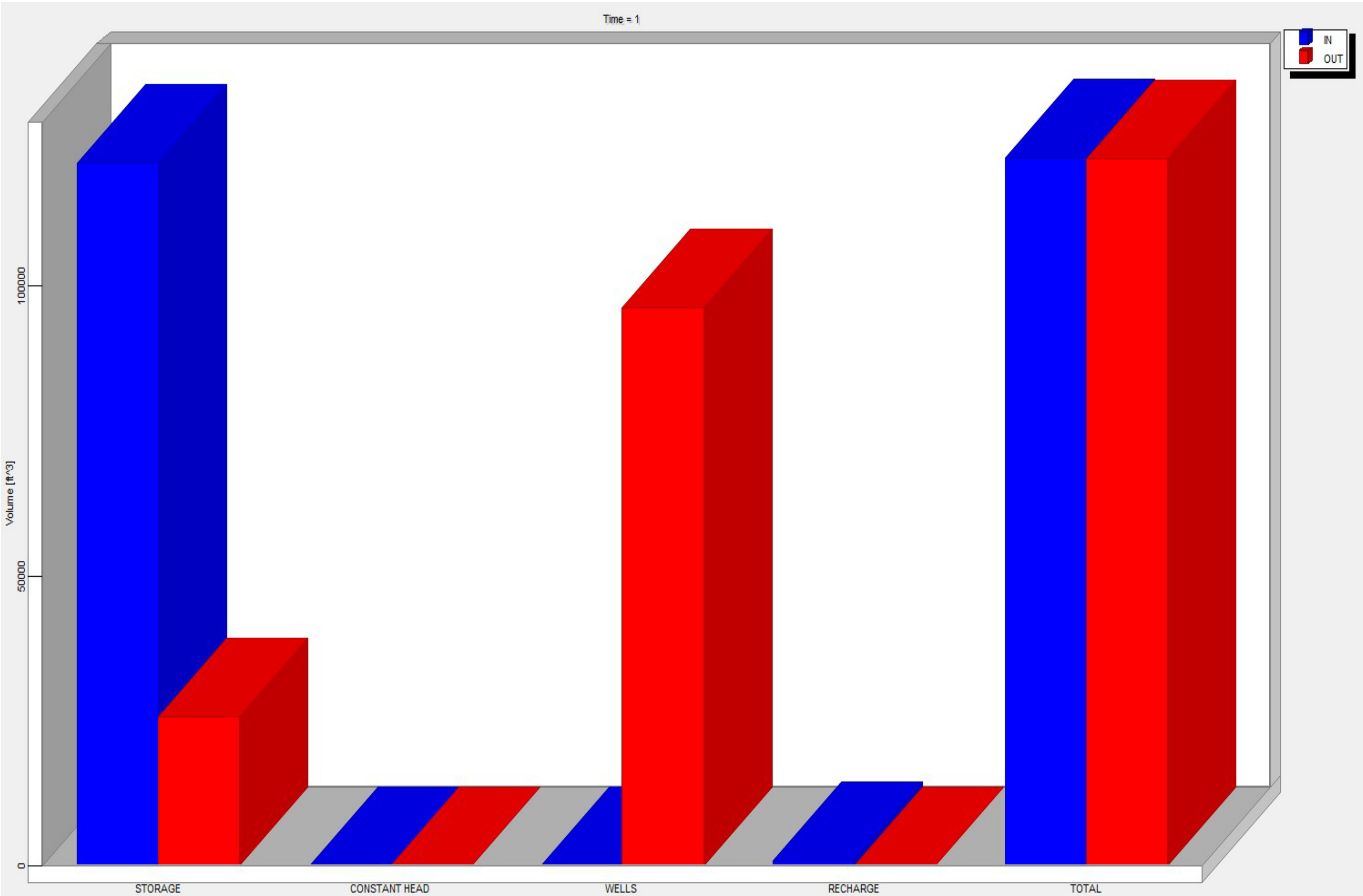


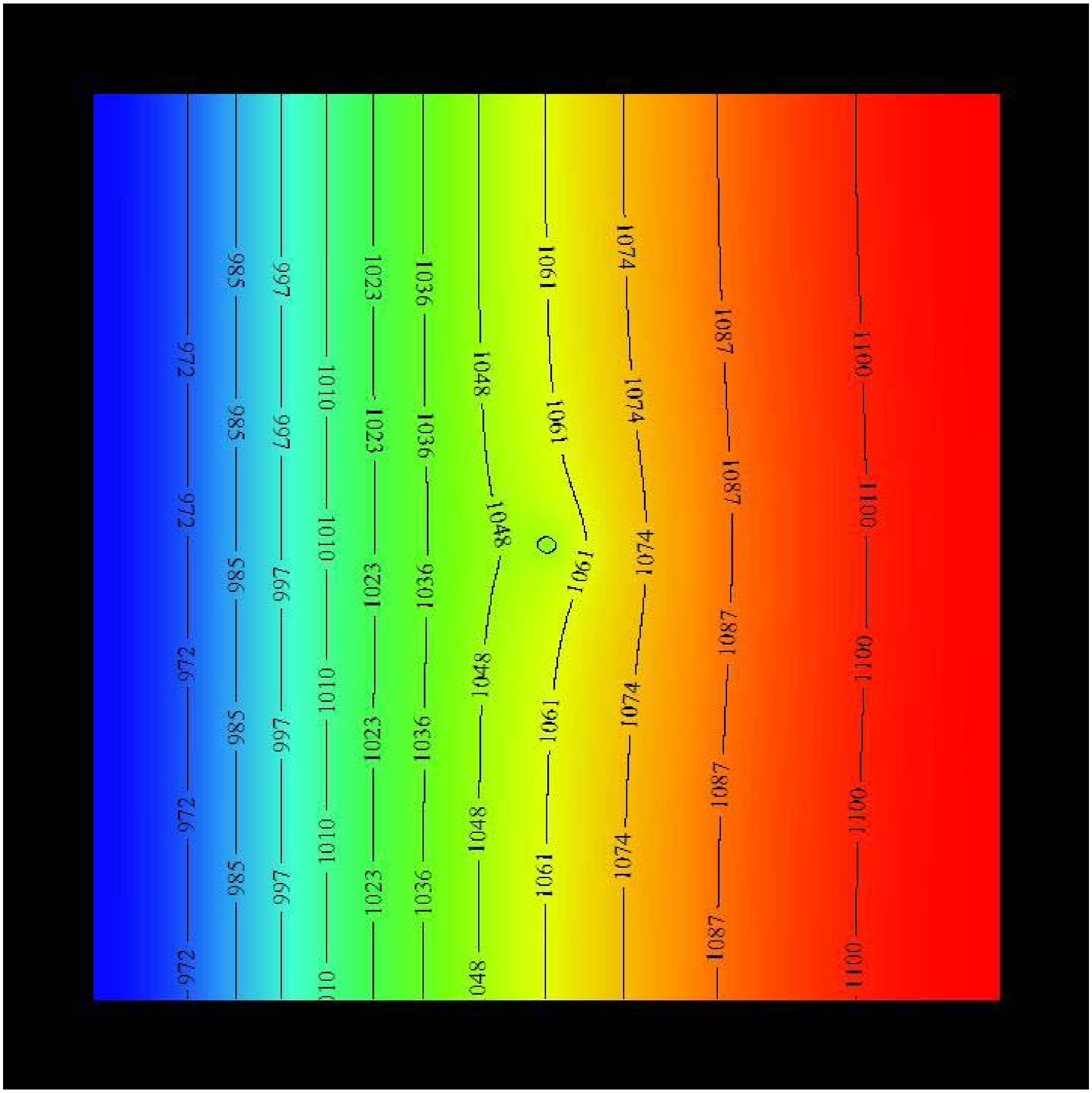
Figure 24. Mass Balance for 4,000 feet by 4,000 feet model with pump time of one day.



vi. 105,600 FEET BY 105,600 FEET MODEL

A twenty mile by twenty mile model was also developed for HI 2. This was done to attempt to eliminate the effect of model boundaries. The model was run for a pump time of ten years and can be seen in Figure 25. The model demonstrates the compounding effect of utilizing large cell sizes. According to the results from other model runs, the cone of depression should be much larger than determined by this model run. Also, the steady state run results utilizing previously determined hydraulic values from smaller model sizes displayed the same issues with uneven head distribution. It was thought that this might be an issue with closure criterion. To test this, closure criterion was reduced to 0.001 and the model was run again. Unfortunately, this did not remedy the situation and an even smaller closure criterion of 0.0001 failed to attain closure.

Figure 25. Result of 105,600 feet by 105,600 feet model run with pumping time of ten years.



3. AQUIFER THICKNESS

As previously discussed, the available information and data are inconclusive regarding actual aquifer thicknesses. It was decided to make the water table elevation equal to the top of the aquifer, but if the aquifer is confined or semi-confined the aquifer thickness could potentially be much smaller than the open borehole length. Thus it is prudent to test multiple aquifer thickness scenarios in order to determine what effect it has on model results. Testing was completed utilizing the recalibrated 21,120 feet by 21,120 feet and 4,000 feet by 4,000 feet models. Models were run utilizing the same aquifer values as in the previous model runs but aquifer thickness was changed to 1,500 feet and 628 feet for two separate test models. The 628 feet thickness was chosen because this is the length of the open borehole for the HI 2 well. The time lengths tested in the model runs were 1 day, 90 days, and 5 years.

Results from these tests were then compared to Figures 14, 15, and 16 which were the result of using an aquifer thickness of 1,037 feet. As would be expected there is no significant difference between the model with an aquifer thickness of 1,500 feet and 1,037 feet since there is little additional groundwater elevation upgradient of the wellhead to be utilized in the thicker aquifer. Figure 26 is a chart displaying head values vs. model time for the three aquifer thickness scenarios tested and Table 23 gives the head values from the model results. A visual comparison between the aquifer thickness runs of 628 and 1,037 feet show a large difference in the overall head value changes.

Figure 26. Chart showing head values vs. time for three modeled aquifer thicknesses and either 500 or 250 GPM well pumping rate with all other aquifer values remaining constant for HI 2 at 21,120 feet by 21,120 feet or 4,000 feet by 4,000 feet model sizes.

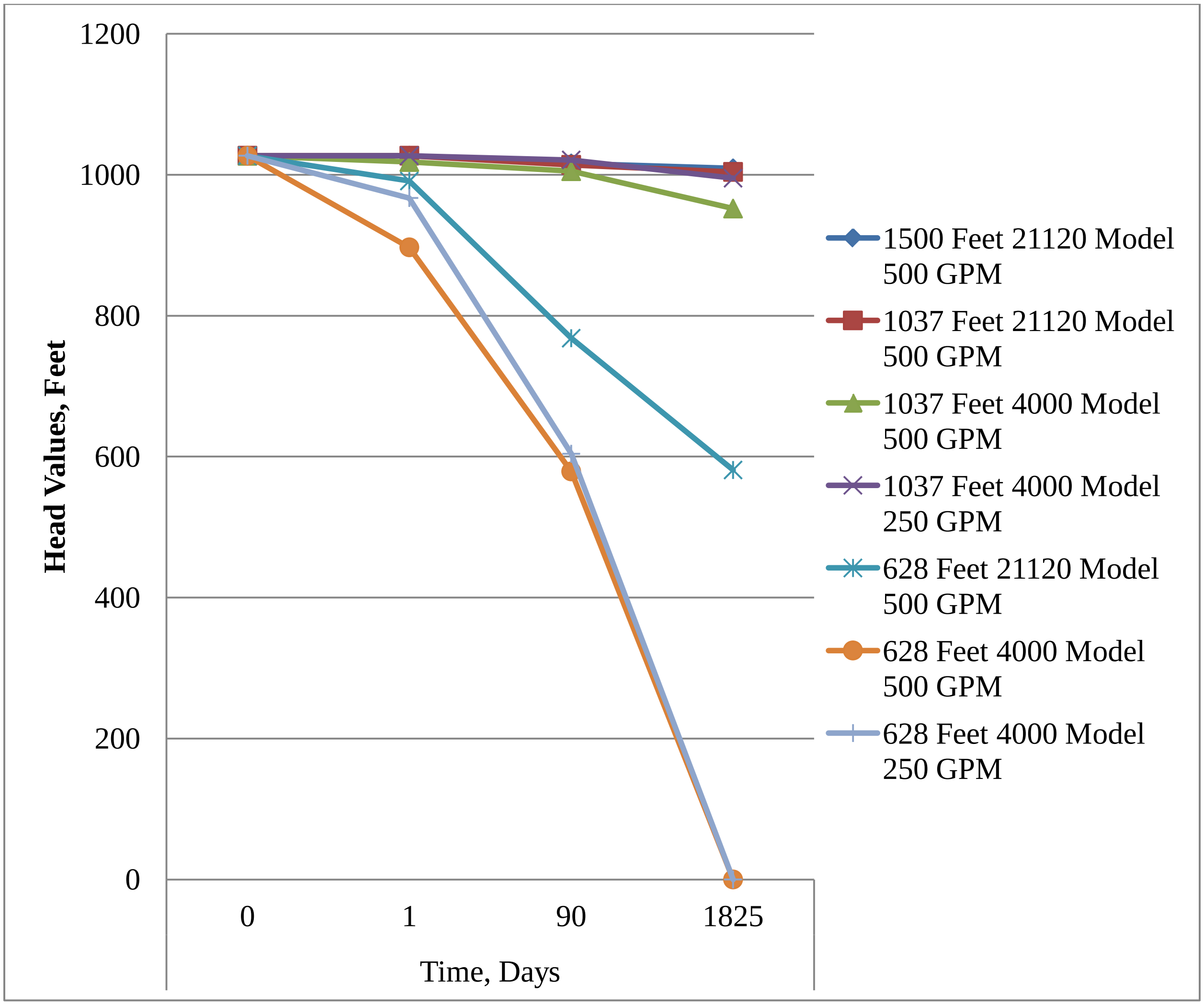


Table 23. Results from modeling runs testing aquifer thickness and pump rate with results listed as head elevations at the wellhead in feet by pumping time. Model run description consists of Aquifer thickness followed by X and Y dimension of model in feet and pumping rate.

	Time, Days			
Model Run	0	1	90	1825
1500 Feet 21120 Model 500 GPM	1027	1027	1016	1009
1037 Feet 21120 Model 500 GPM	1027	1027	1014	1004
1037 Feet 4000 Model 500 GPM	1027	1018	1005	952
1037 Feet 4000 Model 250 GPM	1027	1027	1021	995
628 Feet 21120 Model 500 GPM	1027	991	768	581
628 Feet 4000 Model 500 GPM	1027	897	579	0
628 Feet 4000 Model 250 GPM	1027	967	604	0

4. WELL PUMP RATE

Adjusting the pumping rate of the wells greatly changed the head values of the model as shown in Figure 26. However, the influence of change in pump rate was mitigated by the lack of knowledge about aquifer thickness, true effect of recharge on head values, and error across grid cells. It is known that actual pump rates are variable with higher rates during summer months and lower rates during the rest of the year, as documented in various ADH reports. Reducing the pump rate does directly decrease the size of the capture zone. However, it is prudent to determine worst case scenarios, thus the maximum pump rate was used for modeling.

G. SENSITIVITY ANALYSIS

1. MODEL DIMENSIONS

Model dimensions have a profound influence on model results. Comparisons between the model runs were made to determine the most appropriate dimensions for modeling other wells in the study. Unfortunately, there were drawbacks to every model size tested. Due to the limitations of the model program that were previously discussed compromises were necessary.

A model size of 4,000 feet by 4,000 feet with grid sized of 200 cells by 200 cells resulting in cell size of 20 feet by 20 feet yielded the most appropriate results for deeper wells with higher pumping rates. A size of 4,000 feet by 4,000 feet allows better confidence in shorter pumping time lengths which is critical when considering potential for contaminant impact of the well. Model sizes for wells with potential for surface water impact were sized appropriately for each well's unique situation to best determine surface water influence.

2. AQUIFER THICKNESS

Aquifer thickness does not have any influence when establishing steady state head values. However, it has a profound influence when varied in subsequent transient state model runs. Results of these analyses were listed in Table 23 and charted in Figure 26. For well scenarios where the static water level in the well is substantially higher than the base of the well casing then the question of aquifer thickness becomes important. In wells where the water table is located somewhere in the open portion of the well bore aquifer thickness may not have as much sensitivity. However, with the aquifers penetrated by the wells in this study it is relatively unknown how individual rock layers behave in the overall aquifer system or what the true aquifer thickness really are. This adds a great deal of potential for error in the model results.

3. RECHARGE

Recharge was highly sensitive. When recharge values were too high then head values would be much higher in the center of the steady state model results and would build above the elevation of the upgradient constant head boundary. When recharge was too low the steady state run head results would have uneven distribution. Test models failed to converge when no recharge was provided on some subsequent models of other wells.

After analysis of all the completed models in this study it becomes clear that recharge is not handled effectively by MODFLOW. In order to calibrate a steady state model, relatively small recharge values must be utilized. In subsequent transient state models the same recharge value must be utilized. These values do not appear to provide a high enough value to properly maintain head values. This can create larger cones of depression than what may be found in reality. It was initially thought that drought conditions could be tested to determine the long term viability of the wells. However, with the lack of confidence in both recharge and aquifer thickness values, the results of this modeling would be highly questionable.

4. HYDRAULIC CONDUCTIVITY

Hydraulic conductivity was highly sensitive in the x and y directions. If conductivity was increased to 10 ft/day then the model would not converge. If conductivity was decreased to 0.1 ft/day then the model developed excess head elevation in the center of the model. Conductivity was not sensitive to value changes in the z direction.

5. SPECIFIC YIELD

Specific yield had influence on modeling results; but, results were not as extreme as conductivity or recharge. An excessively low value would result in head buildup in the middle of the steady state model results. Excessively low values resulted in uneven head elevations across the head value results. No significant difference was seen between values of 0.1 and 0.3 in a calibrated model when all other values were kept constant.

6. SPECIFIC STORAGE

Specific storage had no significant effect on steady state head value results when values from 1E-5 to 1E-9 were tested.

7. HEAD BOUNDARIES

Constant head boundaries were utilized to calibrate a steady state model. If the boundaries were activated for transient state model runs with a pumping well then they influenced aquifer flow into the well by providing an infinite source of water.

General head boundaries were put in as a thin polygon in place of the constant head boundaries on transient state models. These were tested on HI 2 and CR 2. In transient state runs with the pumping well the general head boundary had no effect on flow in the system. Thus other models did not include a general head boundary and only utilized head values from prior calibrated steady state runs for initial head boundaries.

Comparison of model results from model runs with activated general head boundaries and no general head boundaries indicated that there was no difference in the resulting head values across the models. This could be for several reasons. Given other errors in the program, there may be an error with how the program is processing the boundary. As the operation manual for the program contains vague directions on how to generate the general head boundary, there could be operator error in creating and activating them properly. Lastly, given the small modeling size, it may be that the wells are reducing the volume of water so quickly that no response from a general head boundary is evident.

8. PUMPING RATES

Well pumping rates have a large influence on resulting transient state head values. Initially in this project it was thought that modeling a variety of pump rates could provide more accurate or informative data. These rates would be determined by using actual rates provided by the water systems as documented in Sanitary Surveys. Since it has been determined that aquifer thickness, conductivity, recharge, and error across grid cells have such large influences on resulting head levels and these values are fairly low in confidence level, further analysis of pump rate effects is highly devalued.

9. RIVER BOUNDARIES

River boundaries were utilized where appropriate on models for wells HI 1, CR 1, and CR 2. Modeling indicated that for shallow wells a relatively small river boundary can make a big difference in head value results. For the deeper well HI 1, a nearby river boundary allowed the well to reach a steady state after five years which did not occur with other Holiday Island wells.

IV. RESULTS

Results from the modeling were divided into two sections. The first section is on wells that are perceived to have no influence by surface water which are wells HI 2, HI 4, HI 5, CR 3, CR 5, and CR 6. The second section was for wells that could have potential for surface water influence and are wells HI 1, CR 1, and CR 2. Topographic maps with locations of the wells follow as Figure 27 for the Holiday Island wells and Figure 28 for the Calico Rock wells.

Figure 27. Topographic map compilation of Holiday Island area with locations of wells. (USGS topographic maps)

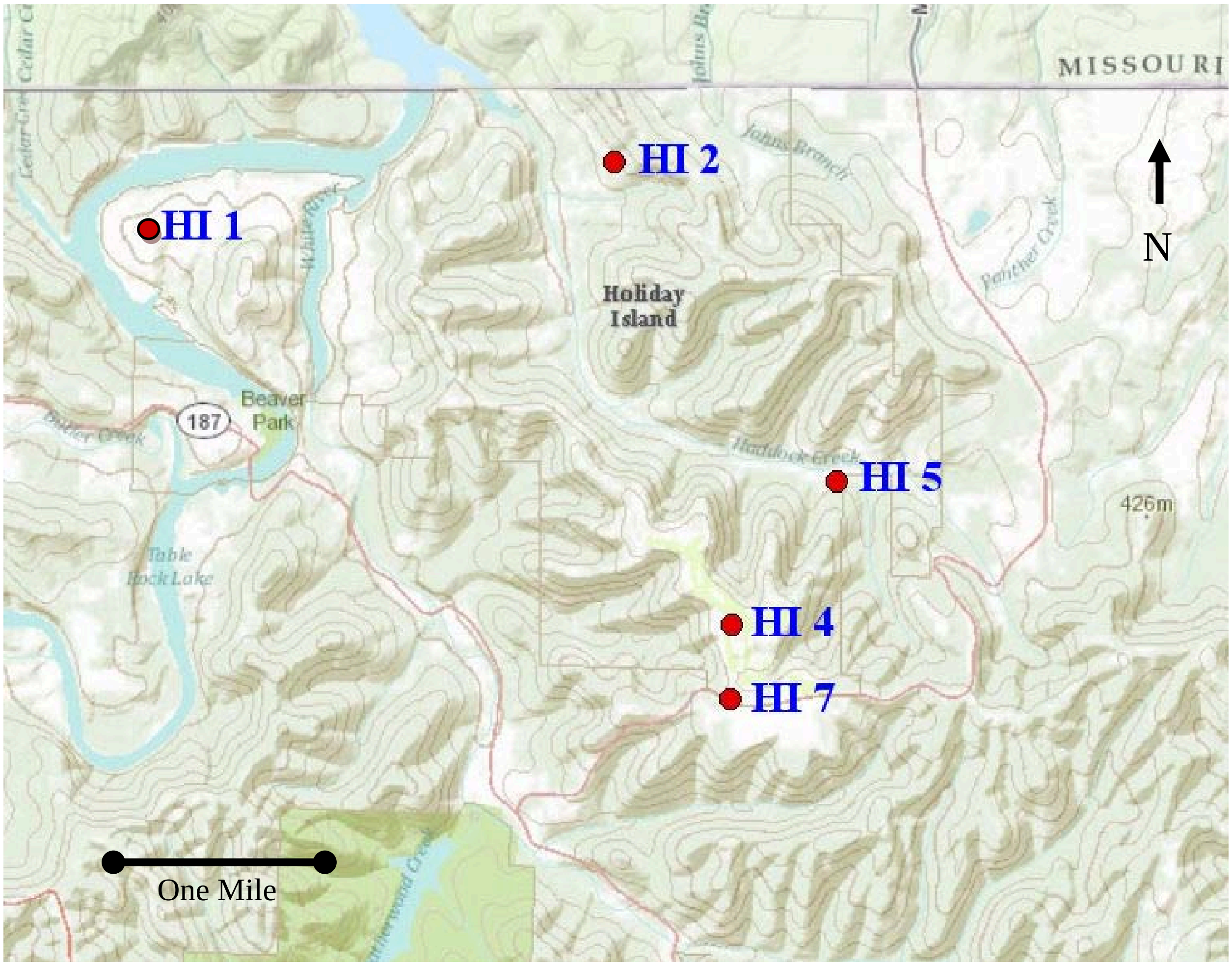
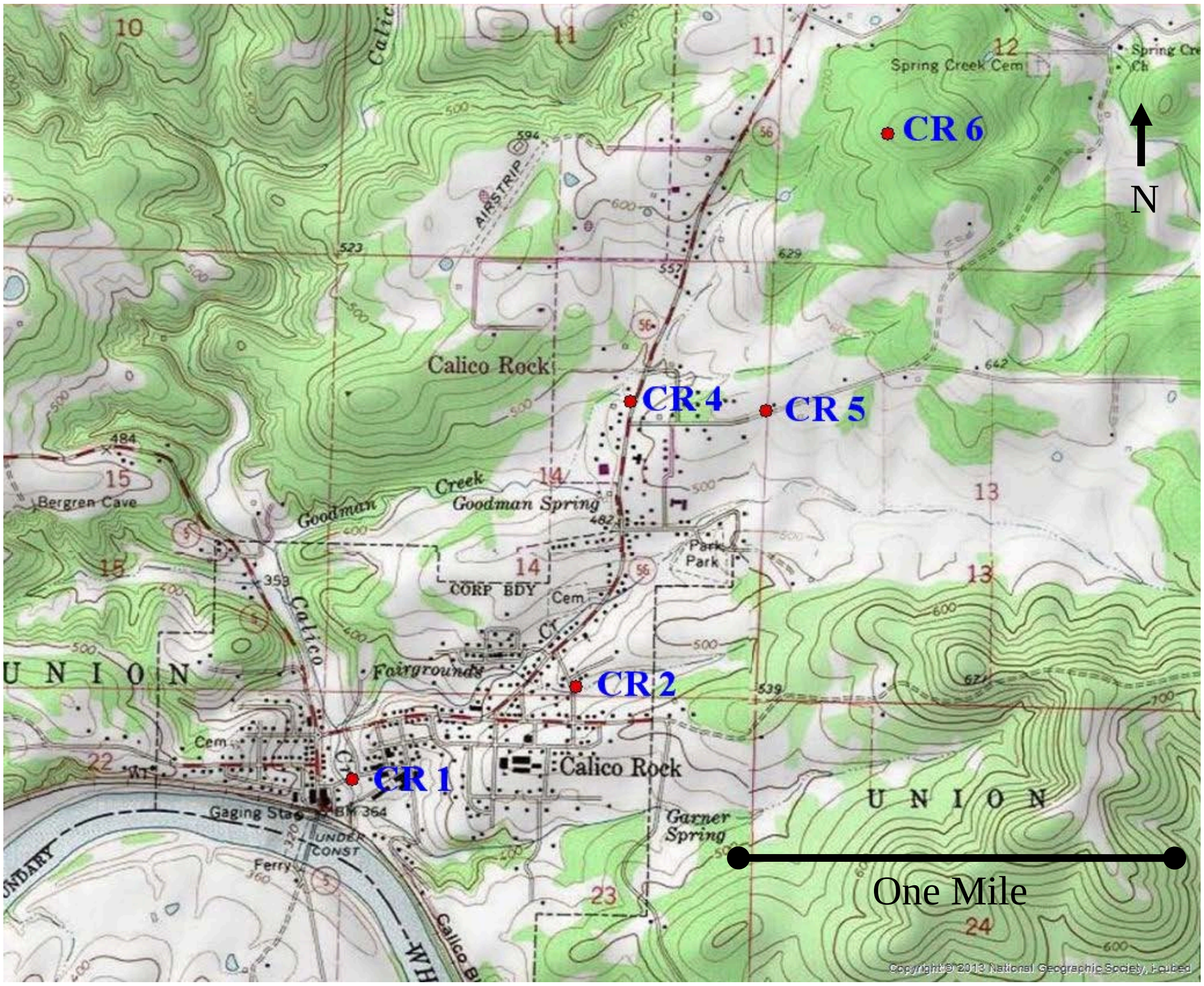


Figure 28. Topographic map compilation of Calico Rock area with locations of wells. (USGS topographic maps)



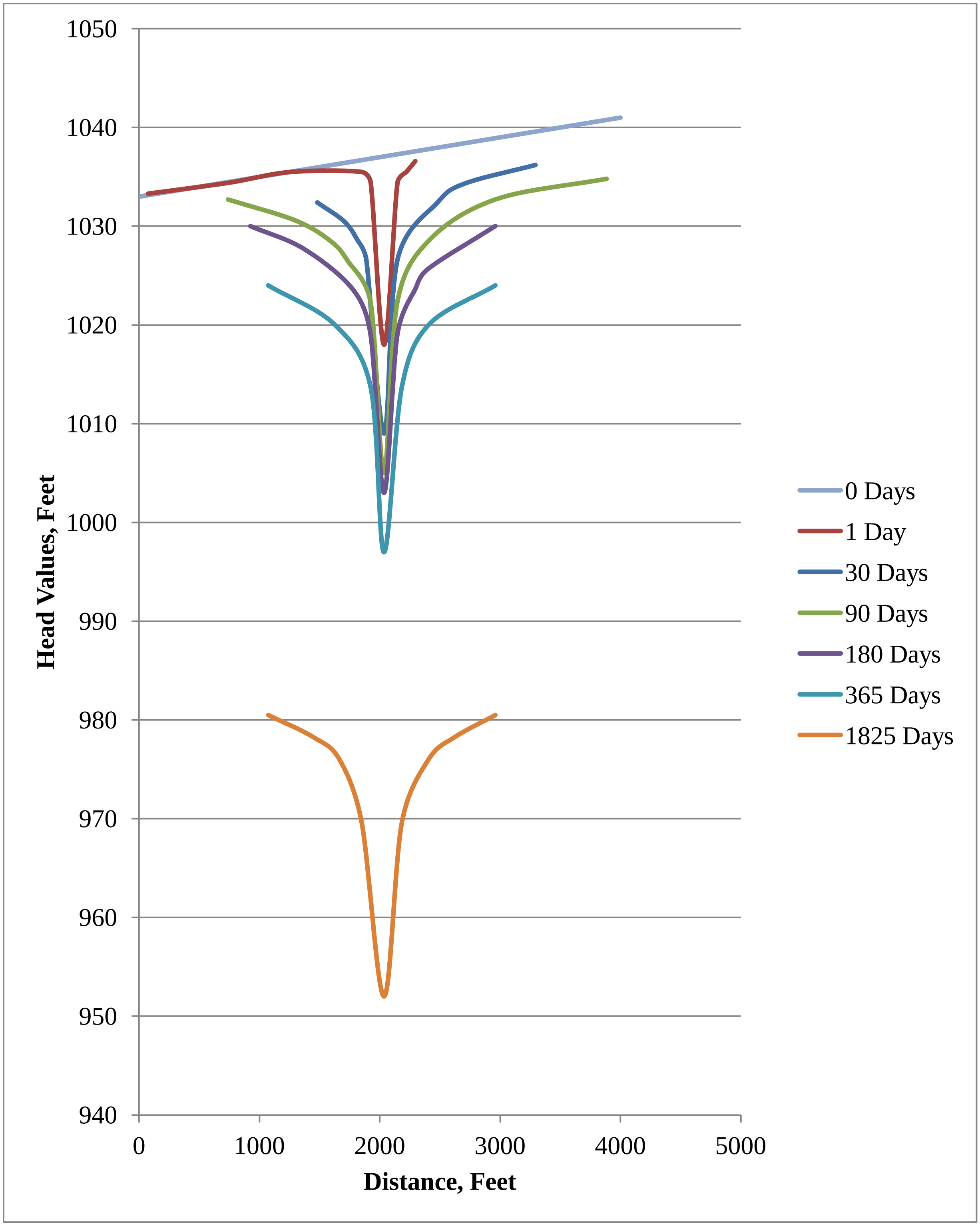
A. MODELS OF WELLS WITH NO SURFACE WATER INFLUENCE

Calibrated aquifer values from the modeling of HI 2 were used in the creation of models for HI 4 and HI 5. For wells CR 3, CR 5, and CR 6 another series of trial and error models were completed in order to generate a calibrated steady state model for initial head values. Model input data for this series of wells are located in Table 24. To appropriately facilitate comparisons between individual wells in this series of models it was necessary to limit of the number of individual modeling runs reported in this thesis. It was decided to include only results from the 30 day pumping time models for this series of wells. However, head values were recorded for each pumping time length, for each well, for comparison included in tables and charts. Results from these wells for the various times are very similar to those displayed for HI 2. Figure 29 contains a series of head values for HI 2. The chart contains a cross section line for each modeling run time which is in the x direction located through the center of the model results. The line begins at the downgradient coordinate (0, 2000) and continues through the well to upgradient coordinate (4000, 2000). Data collected for the completion of this chart are located in Appendix D.

Table 24. Model input data for HI 2, HI 4, HI 5, CR 3, CR 5, and CR 6. X and Y (x, y) locations for all wells were (2000, 2000), model dimensions were 4,000 feet by 4,000 feet. Z up refers to the constant head boundary elevation in the upgradient direction and Z down refers to the constant head boundary elevation in the downgradient direction.

Well ID	Cell Size Feet	K_x K_y ft./ day	K_z ft./day	S_y	Recharge inches	S_s 1/ft.	Z Up Feet	Z Down Feet	Aquifer Thickness Feet	Pump Rate GPM	Well Bottom Elevation Feet	Screen Top Elevation Feet
HI 2	20	3	1.00E-05	0.2	0.25	1.00E-07	1041	1033	1037	-500	0	628
HI 4	20	3	1.00E-05	0.2	0.25	1.00E-07	1364	1356	1360	-500	0	1367
HI 5	20	3	1.00E-05	0.2	0.25	1.00E-07	1042	1034	1038	-500	0	684
CR 4	20	0.3	1.00E-05	0.1	0.25	1.00E-07	589	551	570	-40	0	570
CR 5	20	0.3	1.00E-05	0.1	0.25	1.00E-07	1693	1655	1674	-50	0	1189
CR 6	20	0.3	1.00E-05	0.1	0.25	1.00E-07	1905	1867	1880	-150	0	1520

Figure 29. Cross sectional plot of HI 2 head value information.

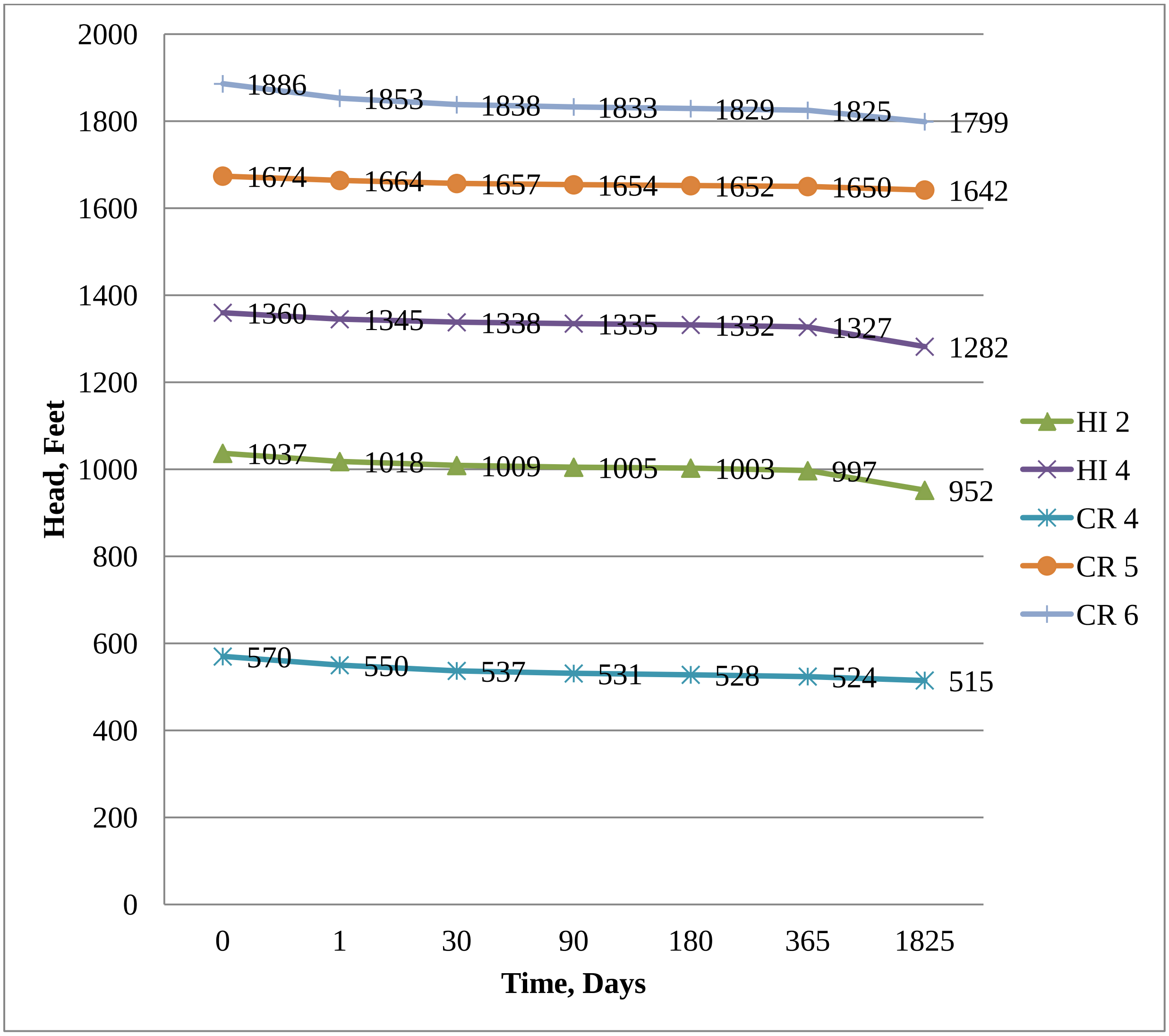


Model information and results for well HI 2 were discussed previously. By coincidence well HI 5 has nearly identical properties to HI 2 after elevations were adjusted for modeling purposes. Head value results from the models are given in Table 25 and a chart of those values is given in Figure 30.

Table 25. Model results as head elevation in feet at the wells for listed modeled pumping time lengths for wells HI 2, HI 4, HI 5, CR 3, CR 5, and CR 6.

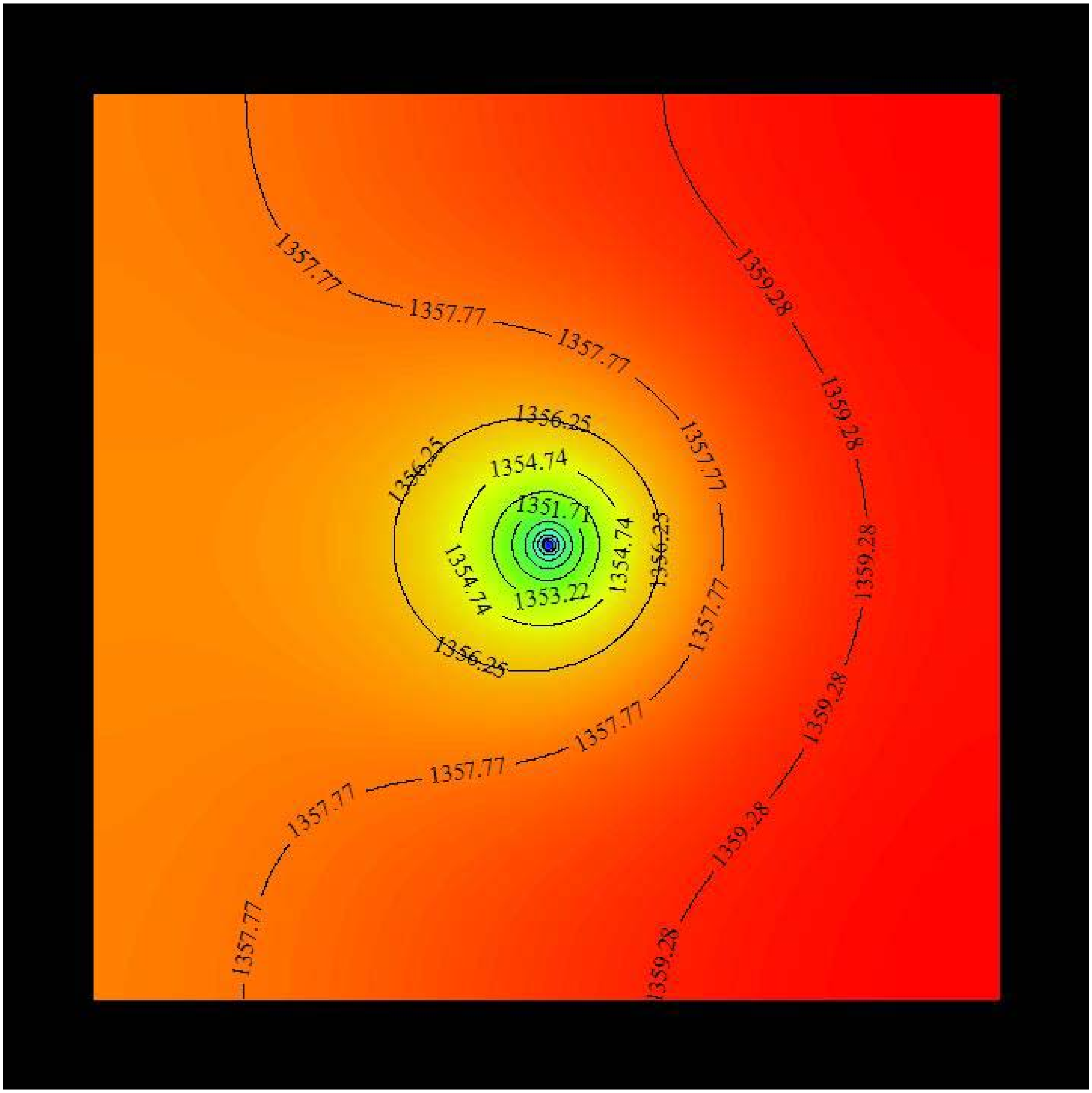
	Time, Days						
Well ID	0	1	30	90	180	365	1825
HI 2	1037	1018	1009	1005	1003	997	952
HI 4	1360	1345	1338	1335	1332	1327	1282
HI 5	1038	1019	1010	1007	1004	998	953
CR 4	570	550	537	531	528	524	515
CR 5	1674	1664	1657	1654	1652	1650	1642
CR 6	1886	1853	1838	1833	1829	1825	1799

Figure 30. Chart showing head values at modeled pumping time lengths for wells HI 2, HI 4, CR 3, CR 5, and CR 6. Well HI 5 was not plotted due to the well having nearly identical results to HI 2.



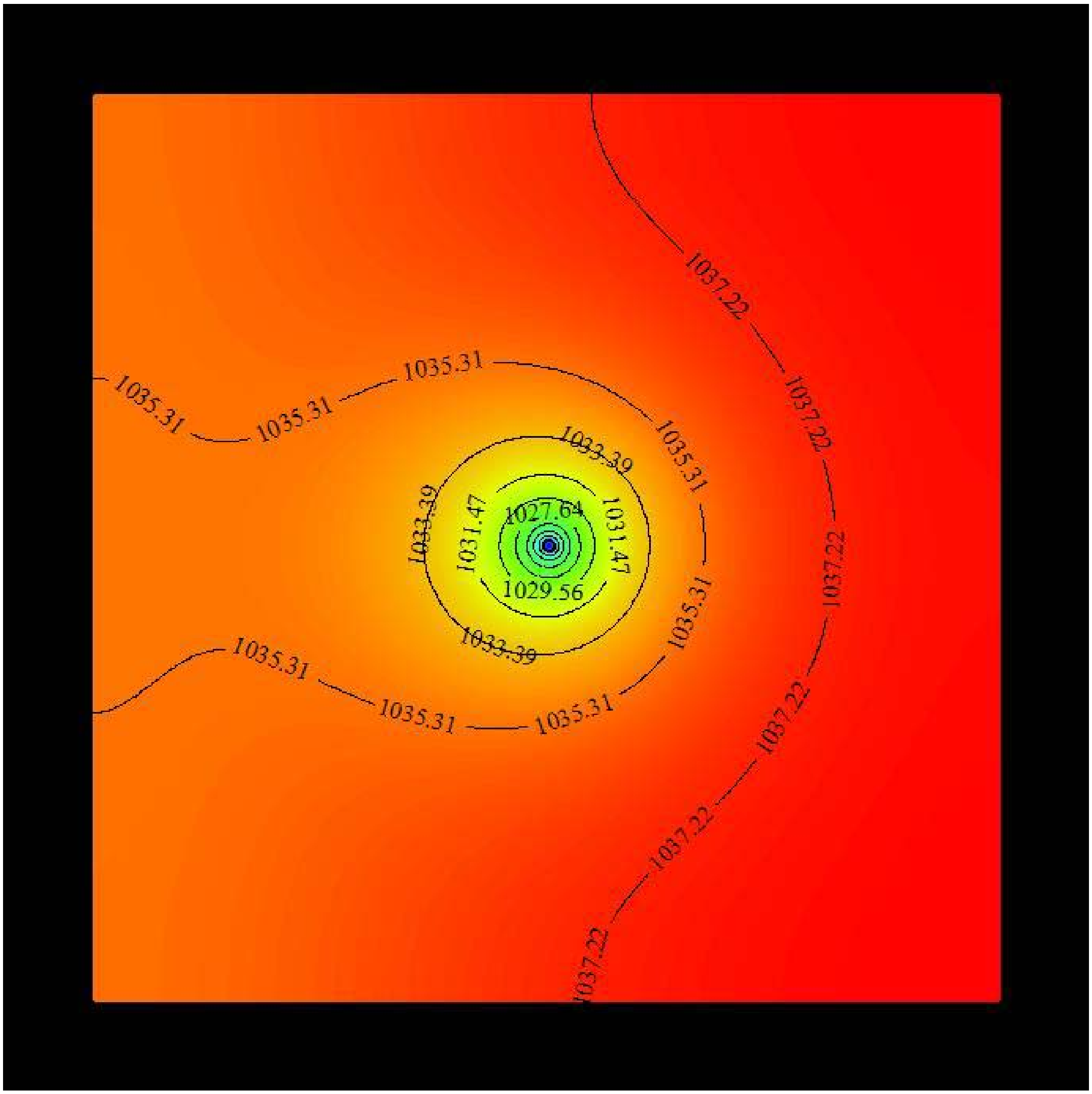
1. HI 4 WELL

Figure 31. Result of transient state model run for HI 4 well with well pumping for 30 days.



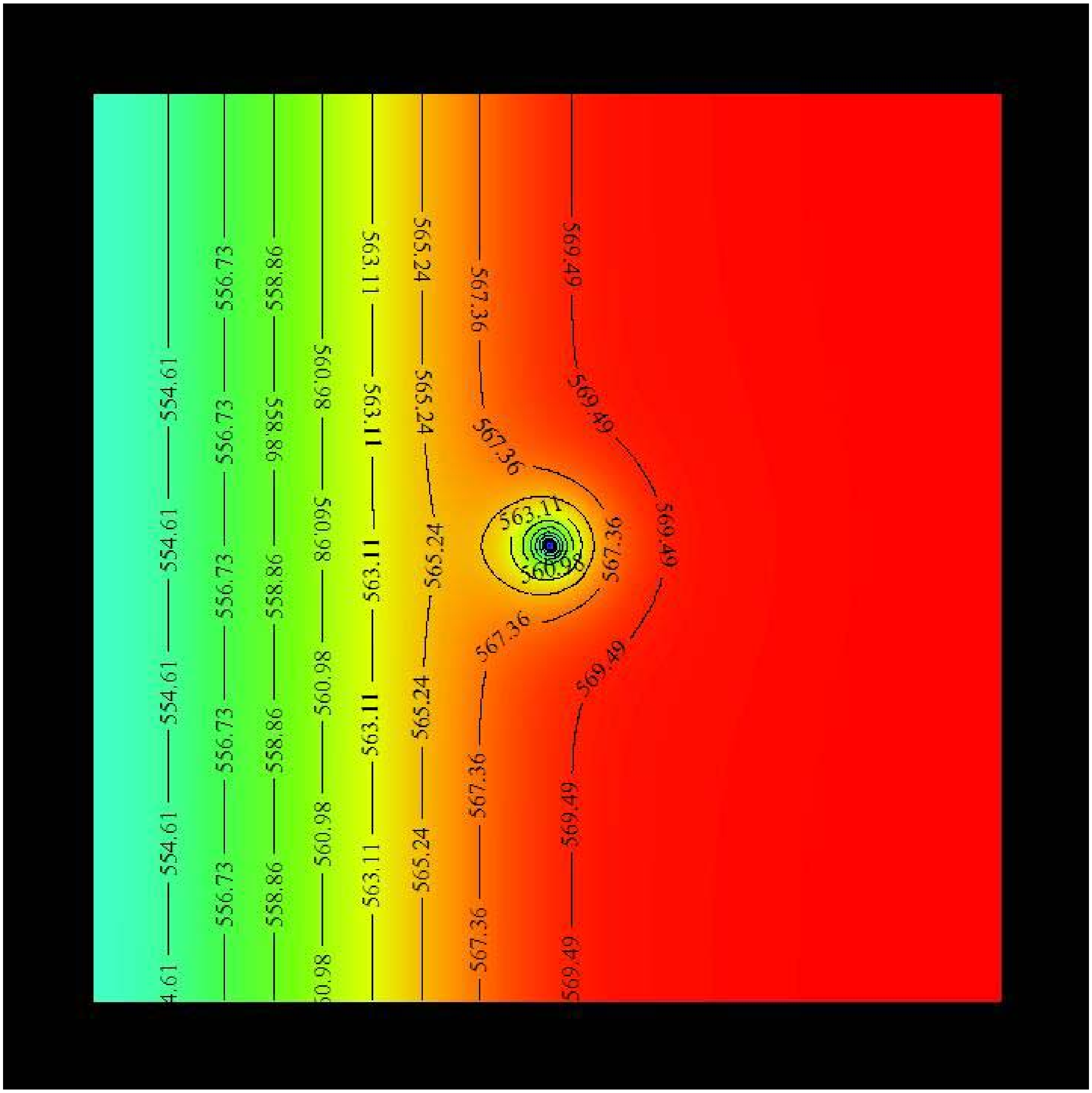
2. HI 5 WELL

Figure 32. Result of transient state model run for HI 5 well with well pumping for 30 days.



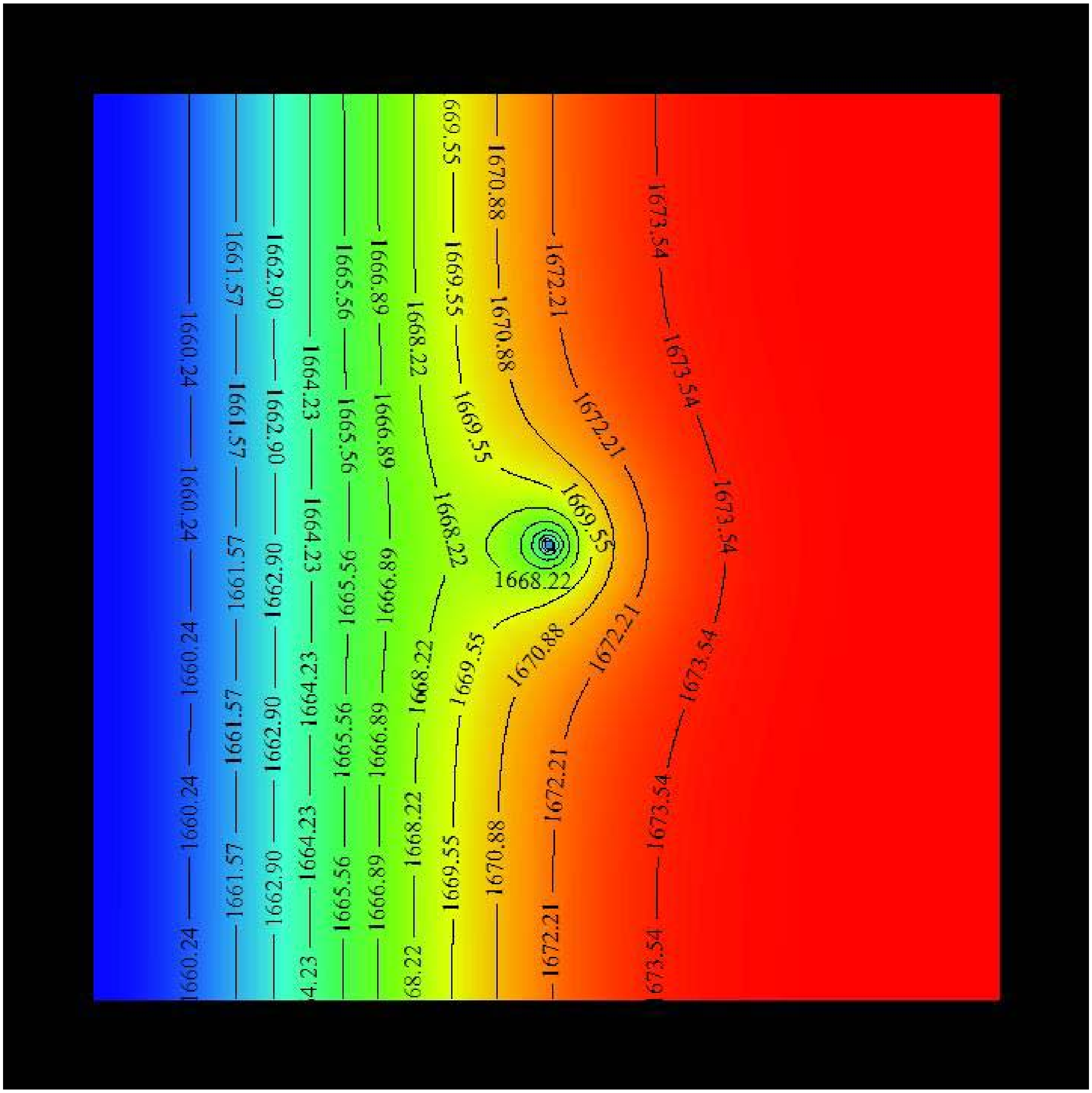
3. CR 4 WELL

Figure 33. Result of transient state model run for CR 4 well with well pumping for 30 days.



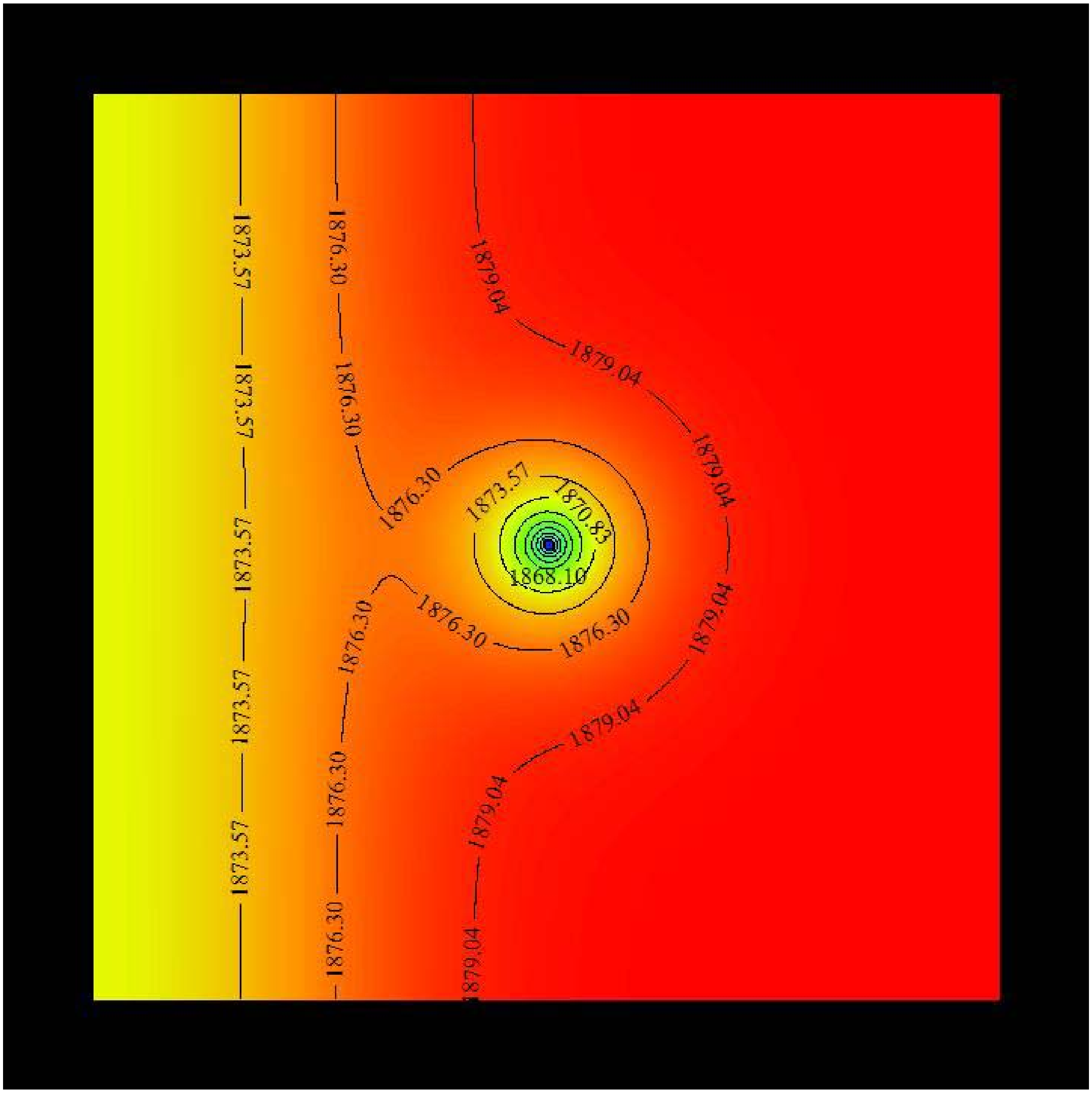
4. CR 5 WELL

Figure 34. Result of transient state model run for CR 5 well with well pumping for 30 days.



5. CR 6 WELL

Figure 35. Result of transient state model run for CR 6 well with well pumping for 30 days.



B. MODELS OF SURFACE WATER INFLUENCED WELLS

Wells with potential surface water impact are HI 1, CR 1 and CR 2. These wells were modeled with river boundaries to determine if augmentation from surface water occurs and the influence it has on the aquifer and pumping wells. Table 26 lists some of the values utilized for the models and Table 28 lists head value results from the models at various time intervals. Figure 36 is a chart of the results of the model as documented in Table 27.

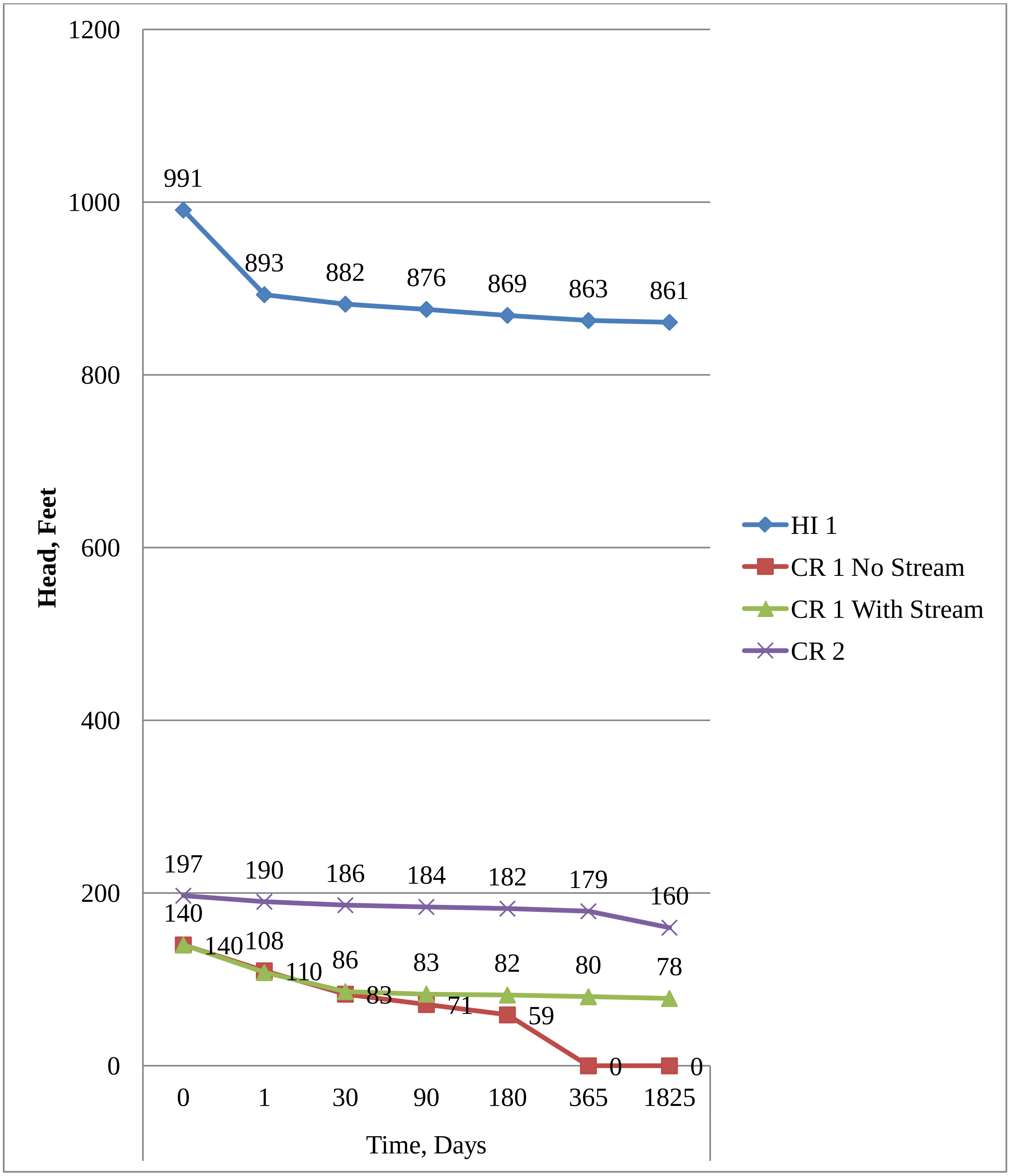
Table 26. Values utilized for HI 1, CR 1, and CR 2 model development.

Well ID	K_x K_y ft./ day	K_z ft./day	S_y	Re-charge inches	S_s 1/ft.	Aquifer Thickness Feet	Pump Rate GPM	Well Bottom Elevation Feet	Screen Top Elevation Feet
HI 1	3	1.00E-05	0.2	0.25	1.00E-06	991	500	0	563
CR 1	3	1.00E-05	0.2	0.25	1.00E-07	200	150	0	140
CR 2	3	1.00E-05	0.2	0.25	1.00E-06	300	50	100	197

Table 27. Results as head elevations in feet at the well from model runs for wells HI 1, CR 1, and CR 2 at listed pumping time lengths.

	Time, Days						
Model ID	0	1	30	90	180	365	1825
HI 1	991	893	882	876	869	863	861
CR 1 No Stream	140	110	83	71	59	0	0
CR 1 With Stream	140	108	86	83	82	80	78
CR 2	197	190	186	184	182	179	160

Figure 36. Chart showing head value results for wells HI 1, CR 1, and CR 2.



1. HI 1 WELL

Head value results from modeling well HI 1 can be seen in Table 28 and subsequent figures. The purple line on individual model results is the river boundary. Initially a test run was completed that included the whole island and surrounding river. This yielded a model size of 8,000 feet by 8,000 feet with a 200 by 200 cell grid and 40 feet by 40 feet cells. A river boundary and constant head boundary were put in approximate locations in the model layout and the model was calibrated to steady state. Transient state runs from this model indicated that a smaller cell size would yield more appropriate results. Thus a one mile by one mile model with 26.4 feet by 26.4 feet cells was developed for the well which was more appropriate and yielded better results.

Layout of the model was completed on a topographic map and the layout map can be seen in Appendix C. A line was put in place across the topographic high of the island, in a roughly north, south direction. To simplify model inputs this line was give a (0, 0) coordinate on the southeast corner and a (5280, 5280) coordinate on the northwest corner. This allowed for a constant head boundary to be placed near the bottom edge of the model from approximate coordinates of (1373, 0) to (3590, 0) correlating to the hilltop of the island with a head value of 1038 feet. Well coordinates were given as (3379, 2640). Head values for areas on the other side of the river were not input into the model to keep the model as simple as possible.

Lines were then drawn on the topographic map that were roughly in the center of the river and coordinates for each connecting point were measured and utilized to draw polylines in MODFLOW. The river attributes were defined in the creation of the boundary by defining values at the start and end point vertices and then the model performs a linear interpolation of these data. Table 28 lists coordinates for the river polyline input. River boundary input information is listed in Table 29 and other model values are listed in Table 26. Once all the inputs were placed into the model it was calibrated to steady state and then head values from the steady state run were utilized for transient state runs with various well pumping times.

Table 28. Coordinates for river boundary input for well HI 1 model.

Point	X	Y
0	0	317
1	2112	3696
2	3590	4224
3	4752	2851
4	5280	0

Table 29. River boundary input information for well HI 1 model.

Location	Stage	Bottom	Thickness	Width	Riverbed K ft./day
Point 0	900	850	1	500	3
Point 4	890	840	1	500	3

Figure 37. Result of steady state model run for HI 1 well.

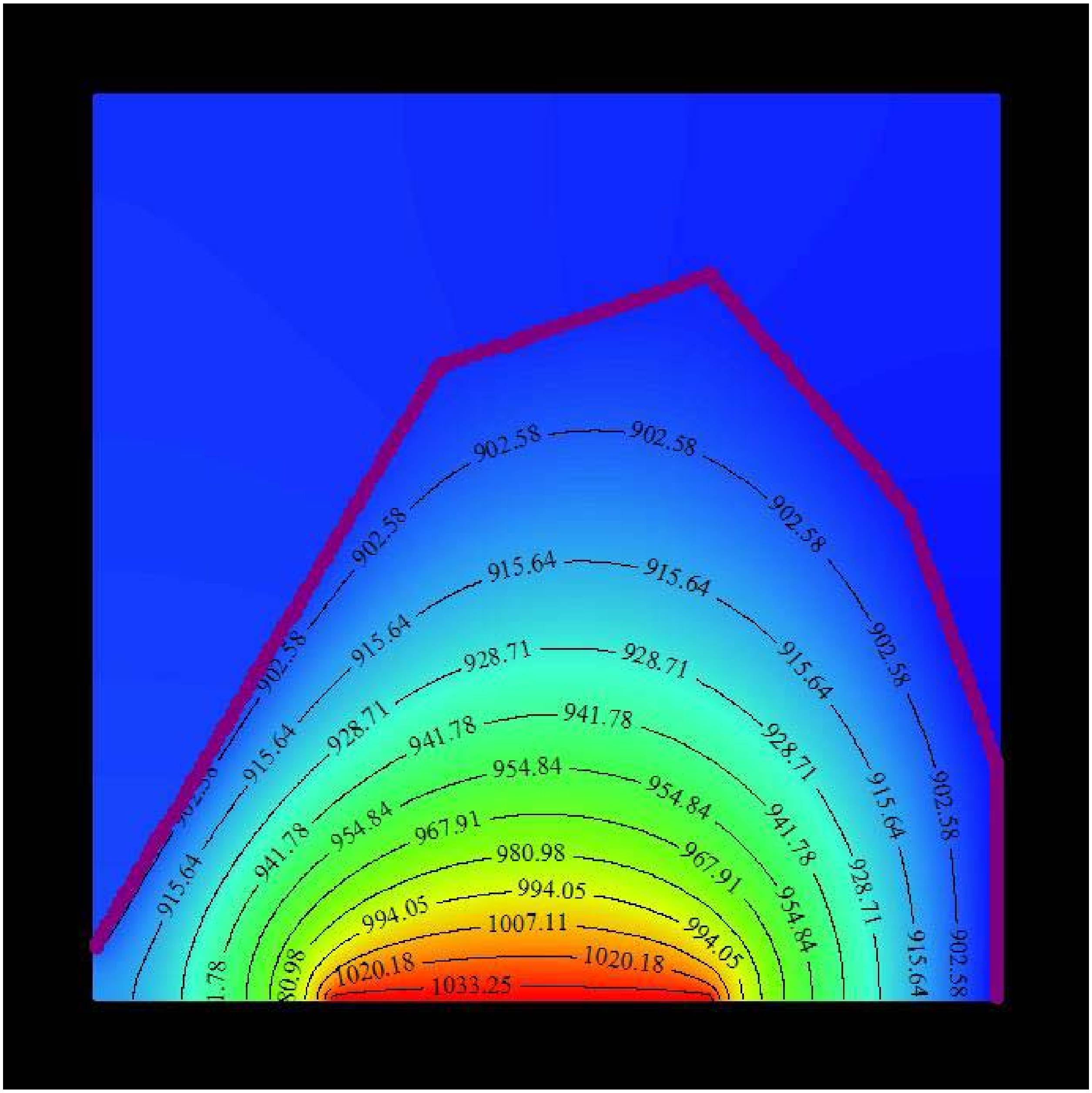


Figure 38. Result of transient state model run for HI 1 well with well pumping for one day.

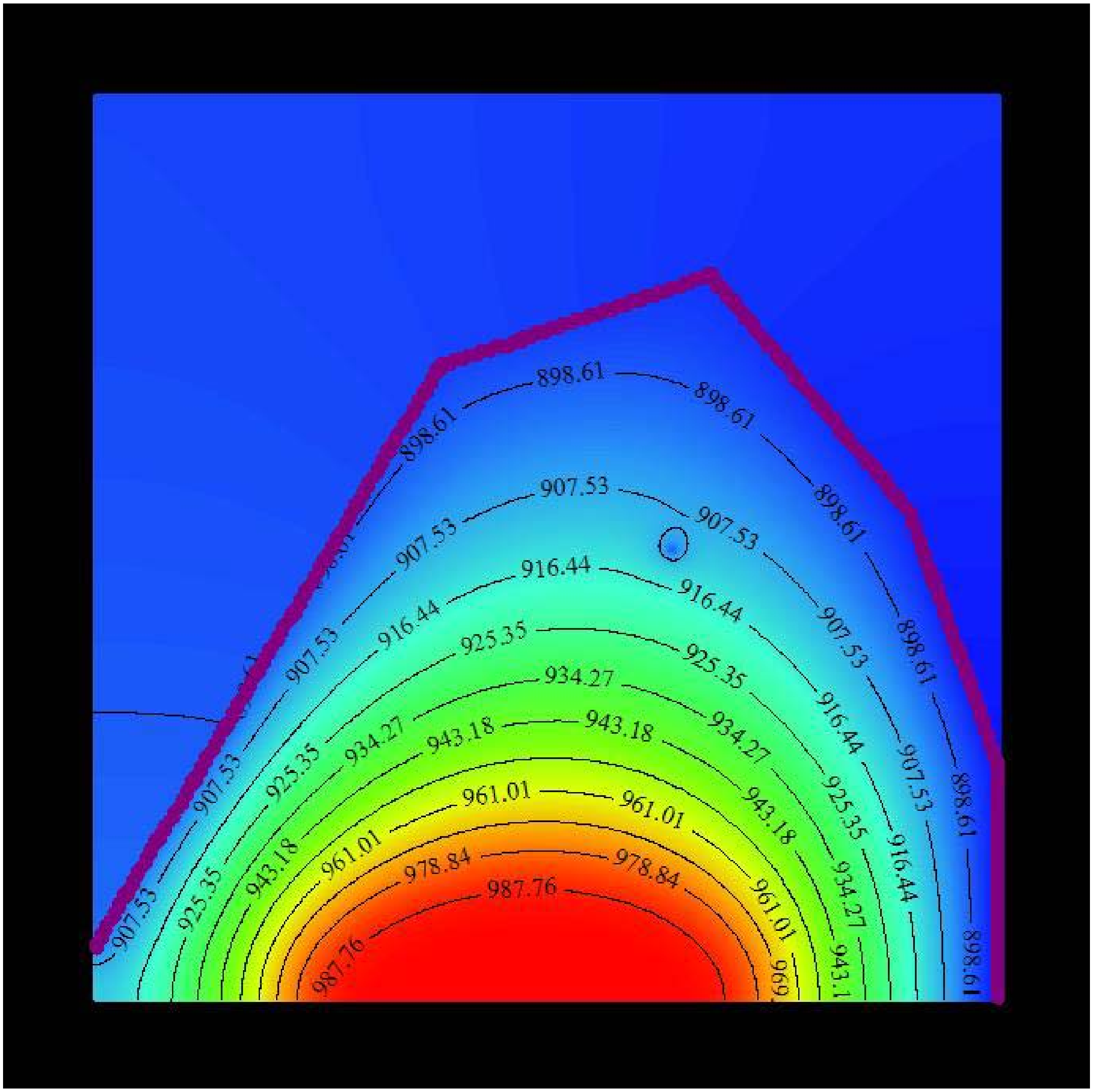


Figure 39.   Result of transient state model run for HI 1 well with well pumping for 30 days.

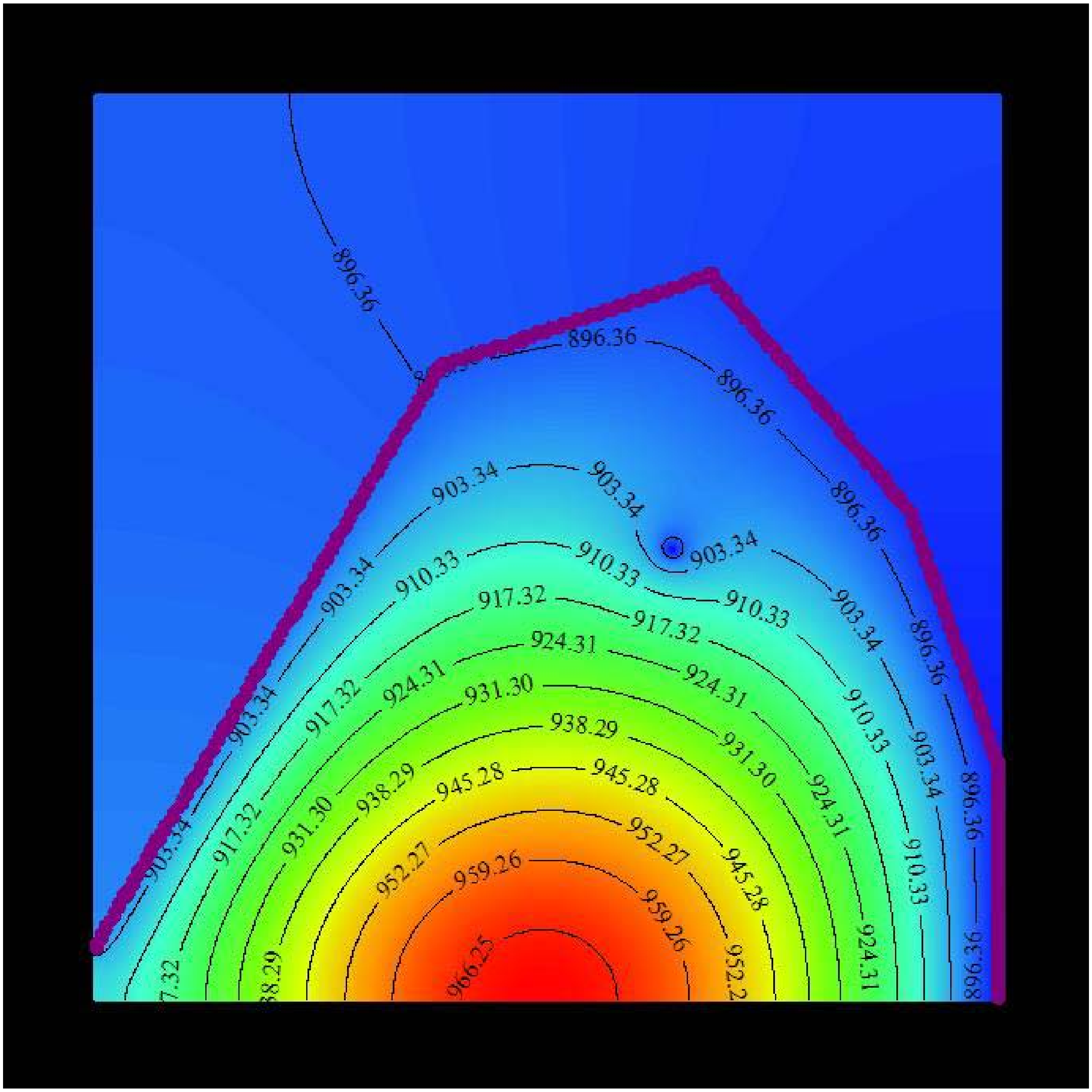


Figure 40. Result of transient state model run for HI 1 well with well pumping for 90 days.

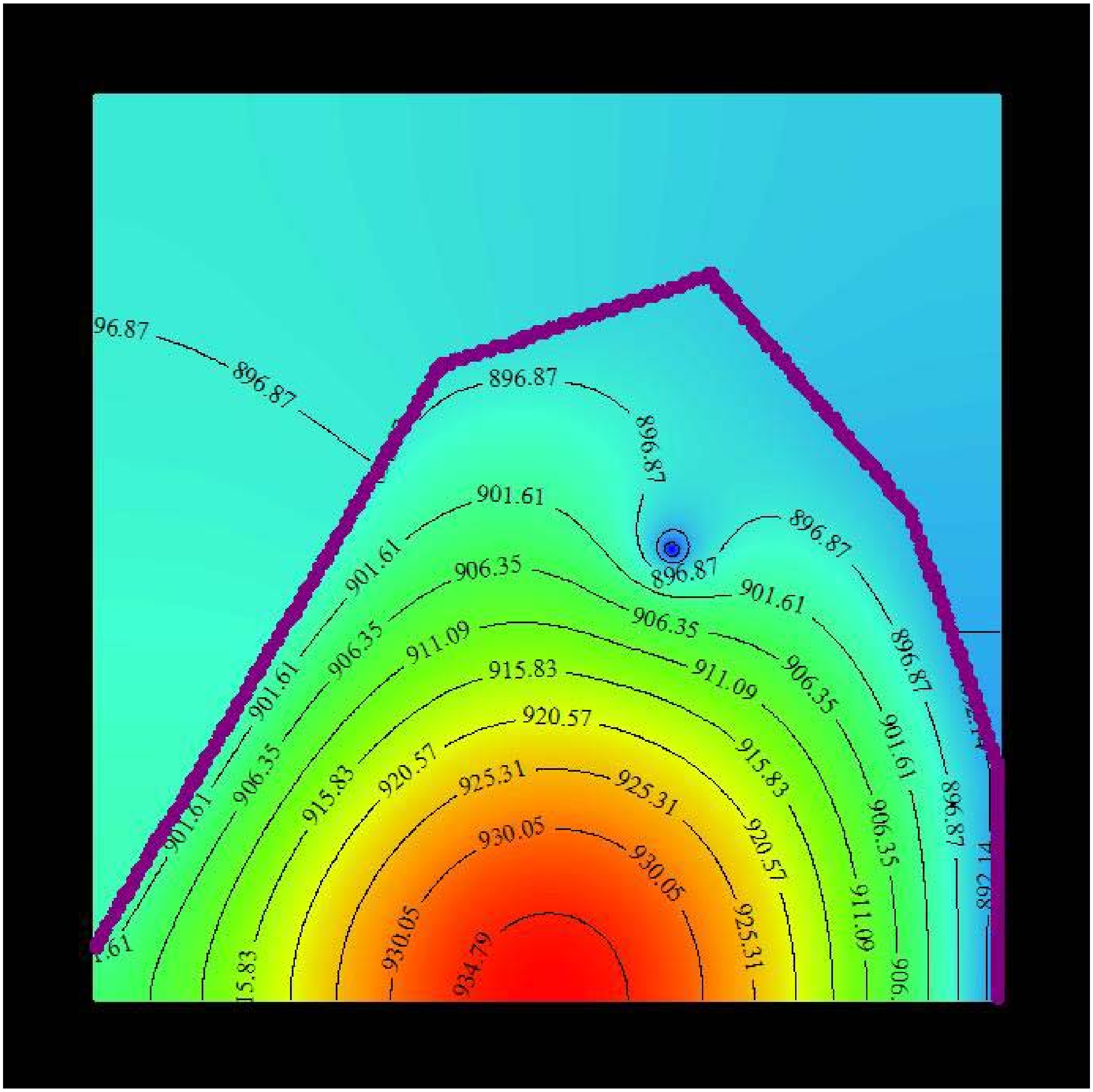


Figure 41. Result of transient state model run for HI 1 well with well pumping for 180 days.

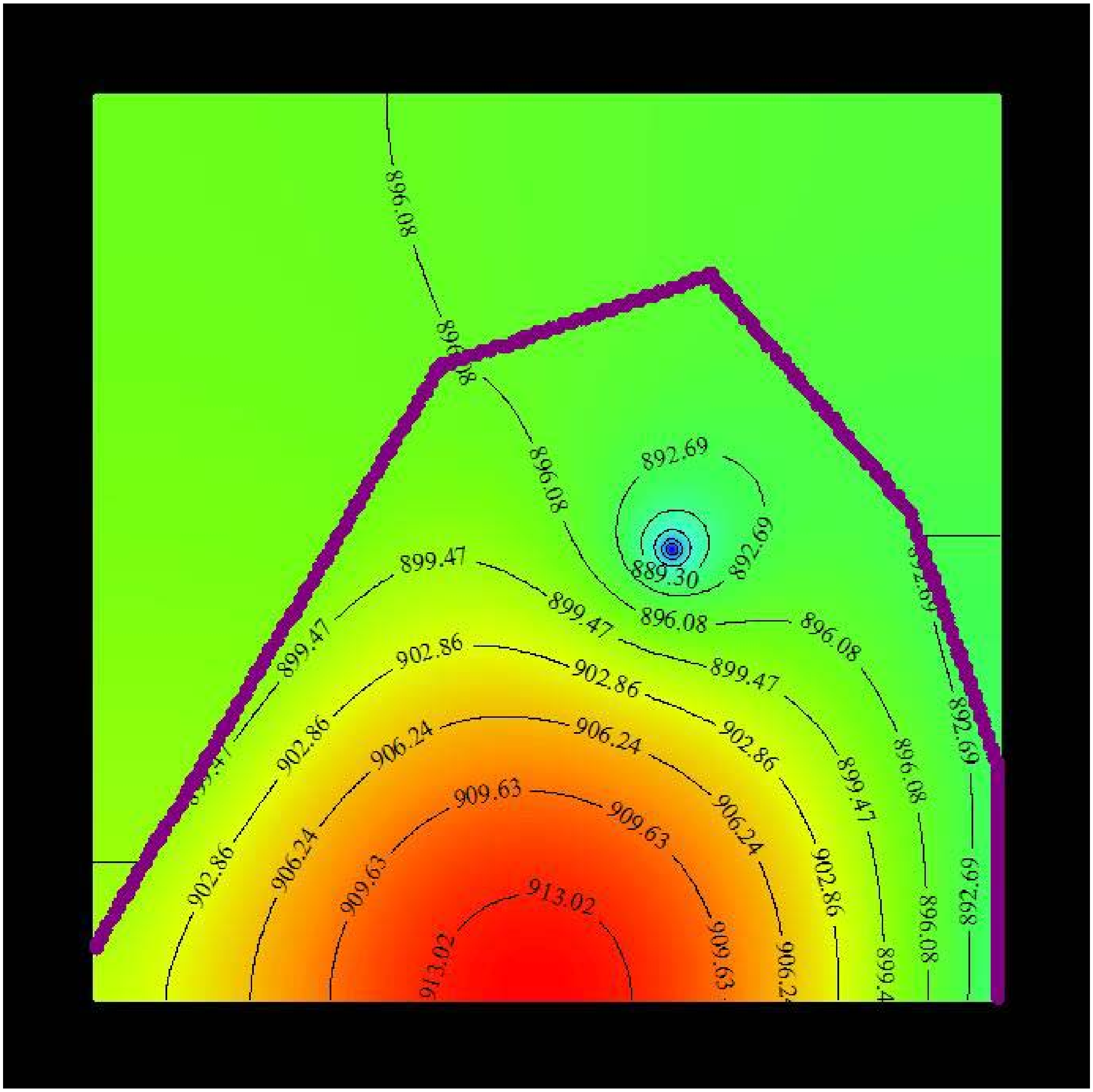


Figure 42. Result of transient state model run for HI 1 well with well pumping for one year.

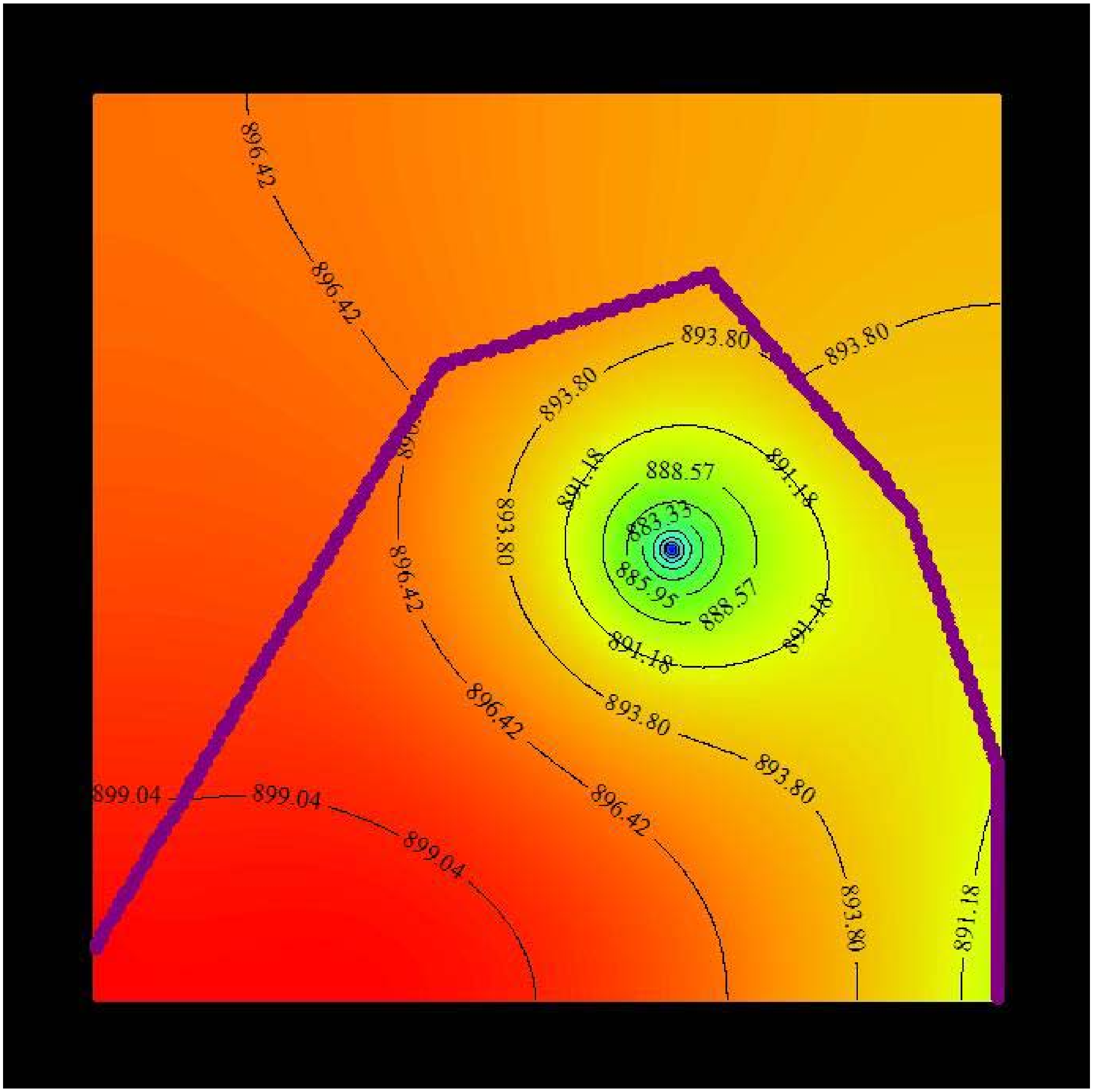


Figure 43. Result of transient state model run for HI 1 well with well pumping for five years.

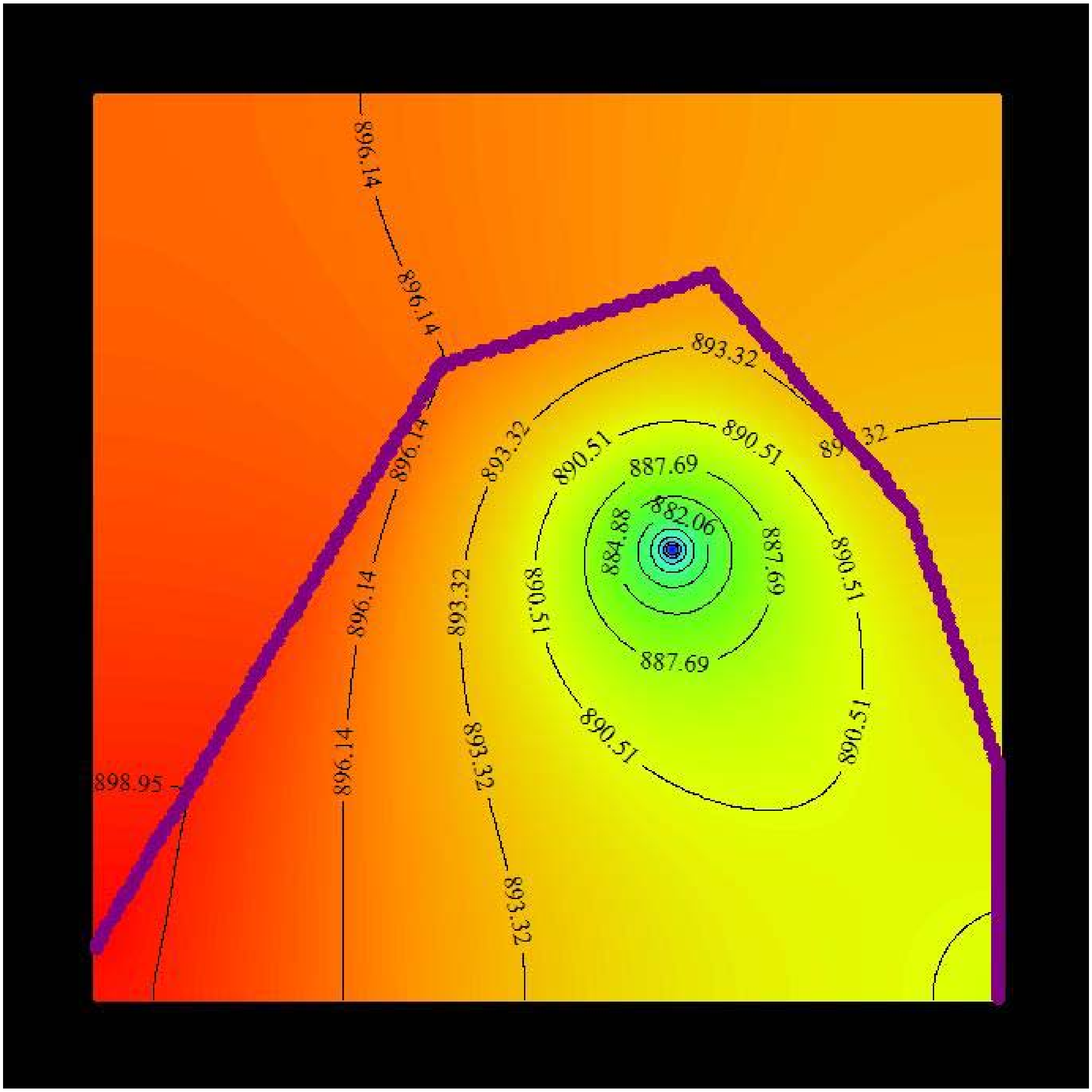
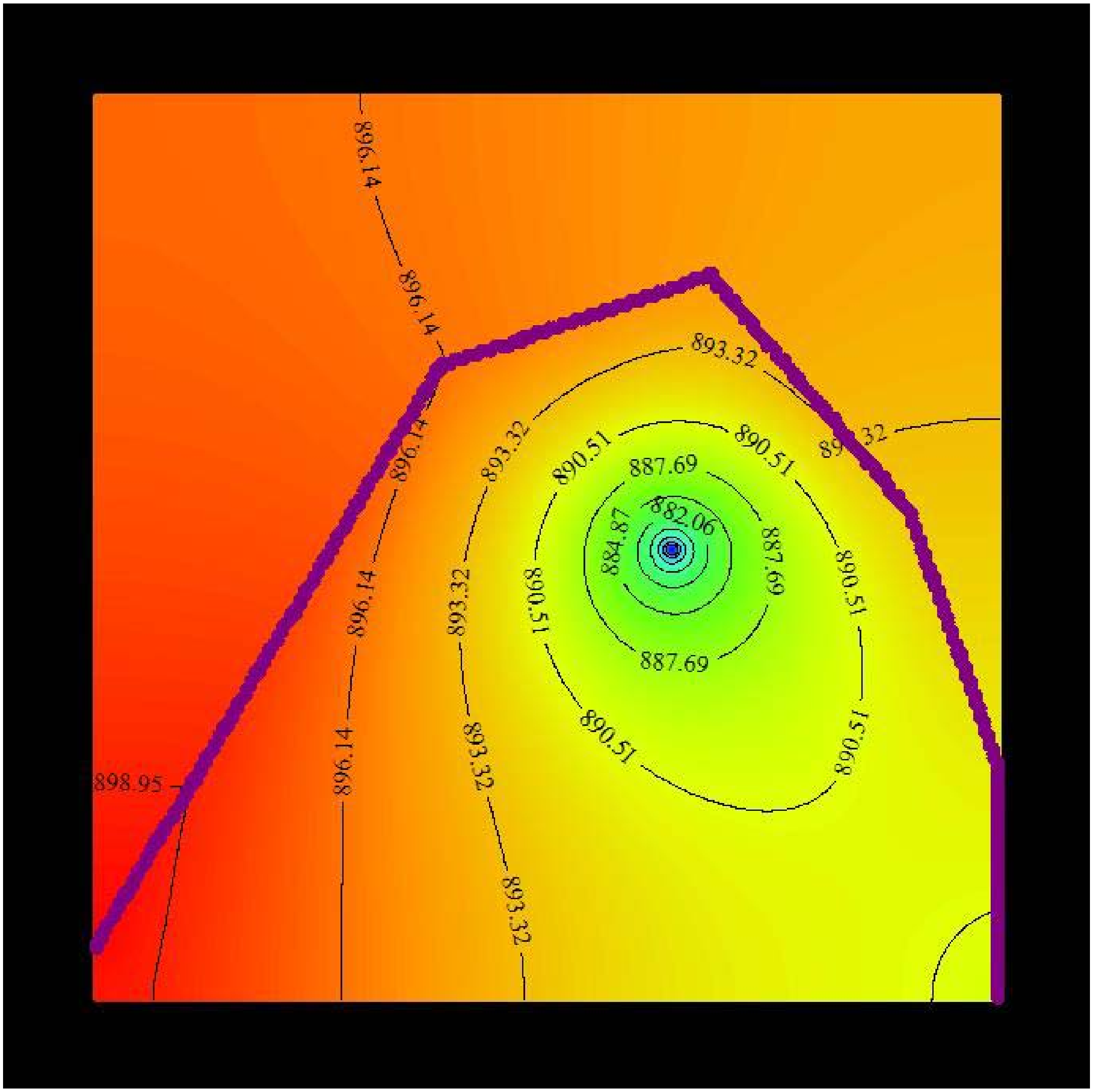


Figure 44. Result of transient state model run for HI 1 well with well pumping for ten years.



2. CR 1 WELL

Results from modeling well CR 1 can be seen in subsequent figures and head values are given in Table 27. Initially some test runs were completed that varied grid dimensions and sizes and positions of the White River. It was determined for the purposes of the model that the White River could be modeled as a straight line across the center of the model. Since constant head values run roughly parallel to the river, especially on a small scale, placing constant head boundaries across the top and bottom of the model simplified the model to generate an appropriate gradient. A model size of 4,000 feet by 4,000 feet with a 200 by 200 cell grid and 20 feet by 20 feet cells was deemed appropriate. Modeling a smaller scale with such a large river proved problematic. Since the CR 1 well is 1000 feet from the White River the coordinates for the well were (2000, 3000).

Initially it was thought that due to the size of the White River it would have considerable influence on the model results. Thus for the first model run only the White River and constant head boundaries were utilized in the steady state model. However, as the data indicates, the well went dry for the one and five year model runs. It is documented in several ADH reports that the well does continuously supply 150 GPM and has done so since 1935. Therefore, it was decided to add Calico Creek as another river boundary for another model run. Modeling inputs for the White River and Calico Creek locations are listed in Tables 30 and 31 respectively and river boundary conditions are listed in Tables 32 and 33 respectively. The river attributes were defined in the creation of the boundaries by defining values at the start and end point vertices and then the model performed a linear interpolation of these data.

Table 30. Coordinates for White River boundary inputs for CR 1 model.

Point	X	Y
0	0	2000
1	2000	4000

Table 31. Coordinates for Calico Creek river boundary inputs for CR 1 model.

Point	X	Y
0	875	4000
1	1600	3350
2	1750	3000
3	2150	2750
4	2450	2000

Table 32. White River boundary input information for CR 1 model.

Location	Stage	Bottom	Thickness	Width	Riverbed K ft./day
Point 0	130	110	1	500	3
Point 1	128	108	1	500	3

Table 33. Calico Creek river boundary input information for CR 1 model.

Location	Stage	Bottom	Thickness	Width	Riverbed K ft./day
Point 0	154	149	1	10	3
Point 4	131	121	1	20	3

Constant head boundaries were put in across the top and bottom of the models and given head values of 157 feet so flow would move downgradient to the river boundary that was placed in the center of the models. The models were calibrated to steady state. Model layout of Calico Creek was completed on a topographic map and the layout map can be seen in Appendix C. Once all the inputs were made into the models they were calibrated to steady state and then head values from the steady state runs were utilized for transient state runs with various well pumping times.

Figure 45. Result of steady state model run for CR 1 well with river only.

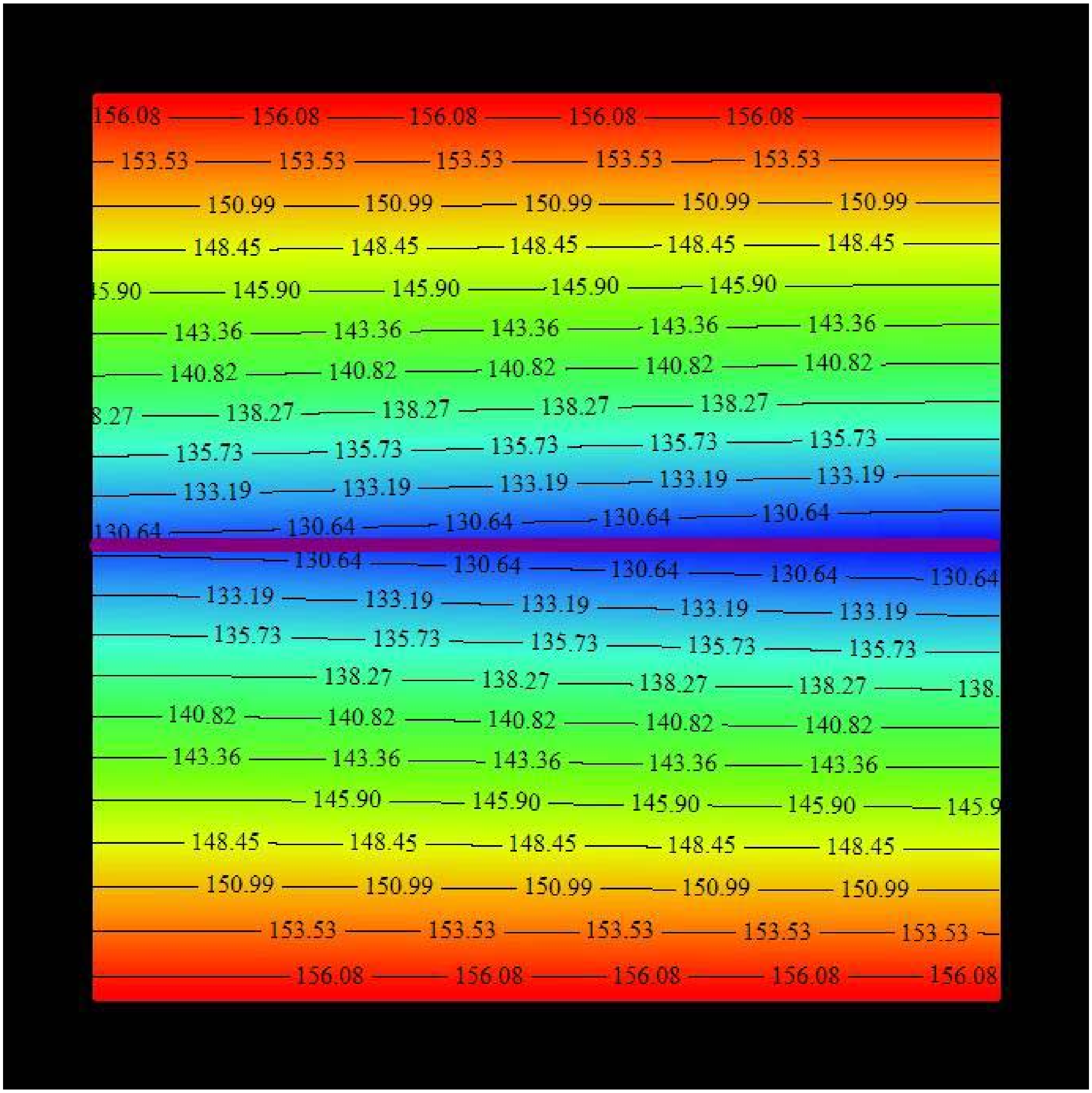


Figure 46. Result of steady state model run for CR 1 well with river and stream.

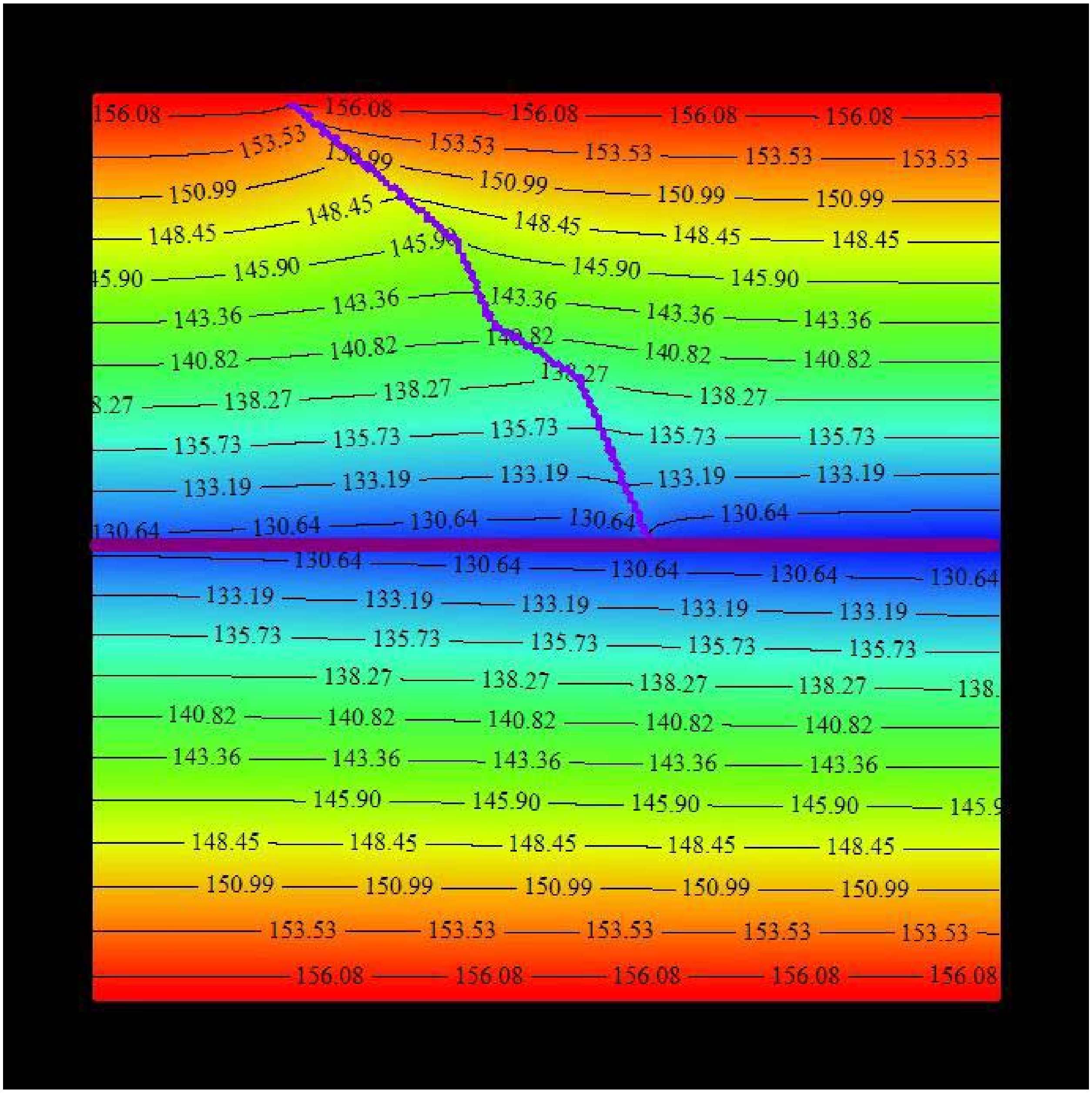


Figure 47. Result of transient state model run for CR 1 well with well pumping for one day with river only.

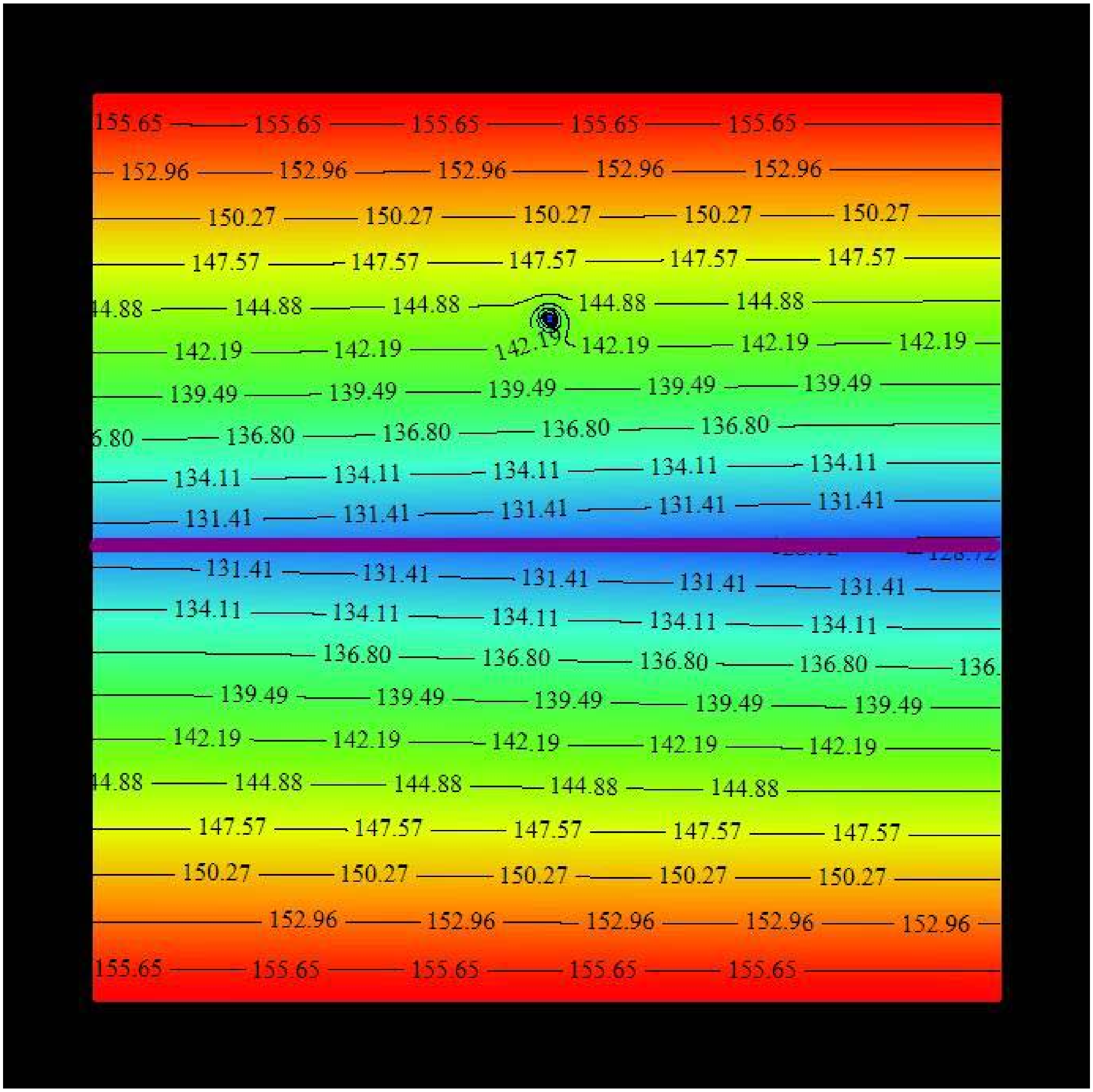


Figure 48. Result of transient state model run for CR 1 well with well pumping for one day with river and stream.

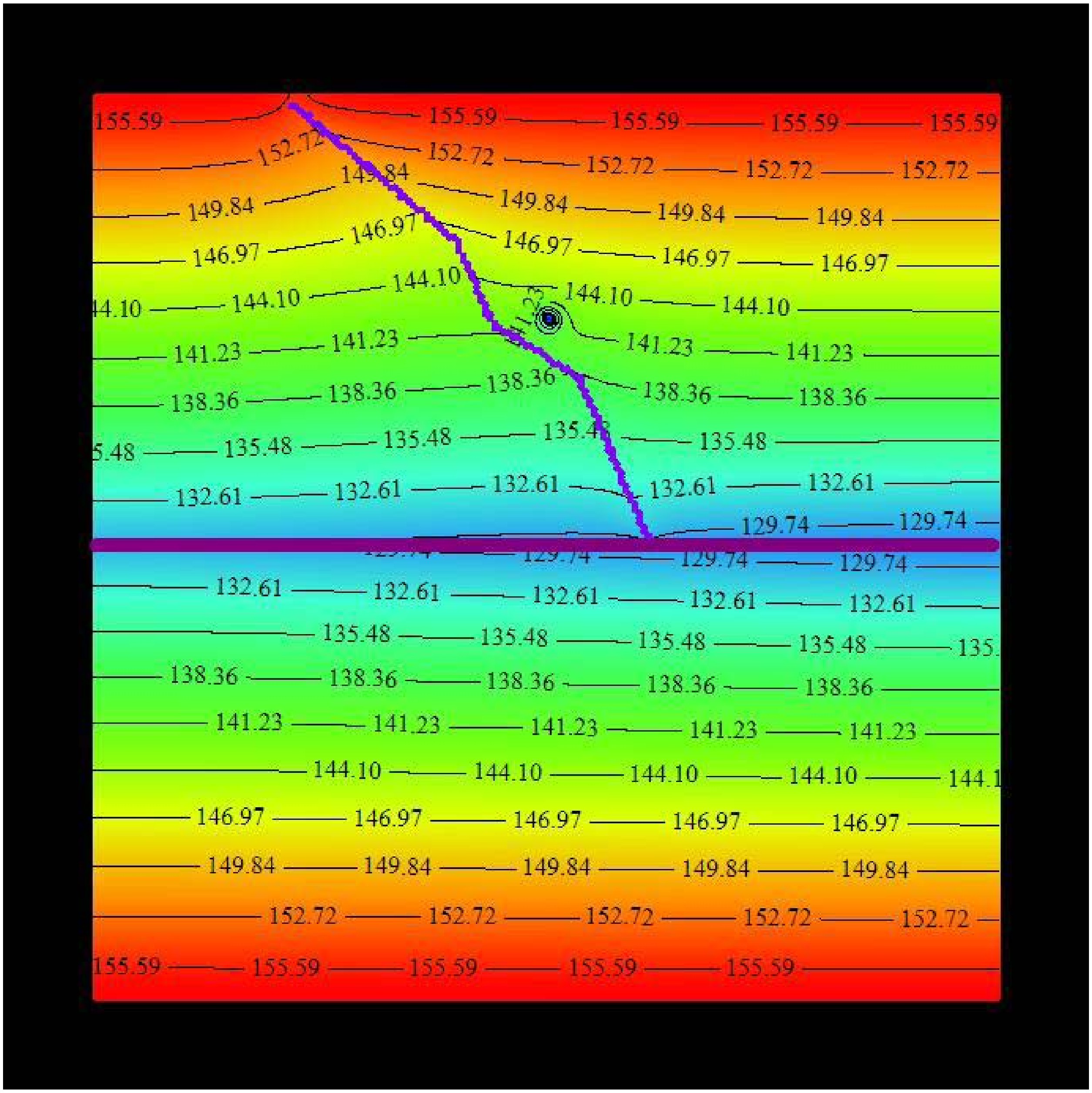


Figure 49. Result of transient state model run for CR 1 well with well pumping for 30 days with river only.

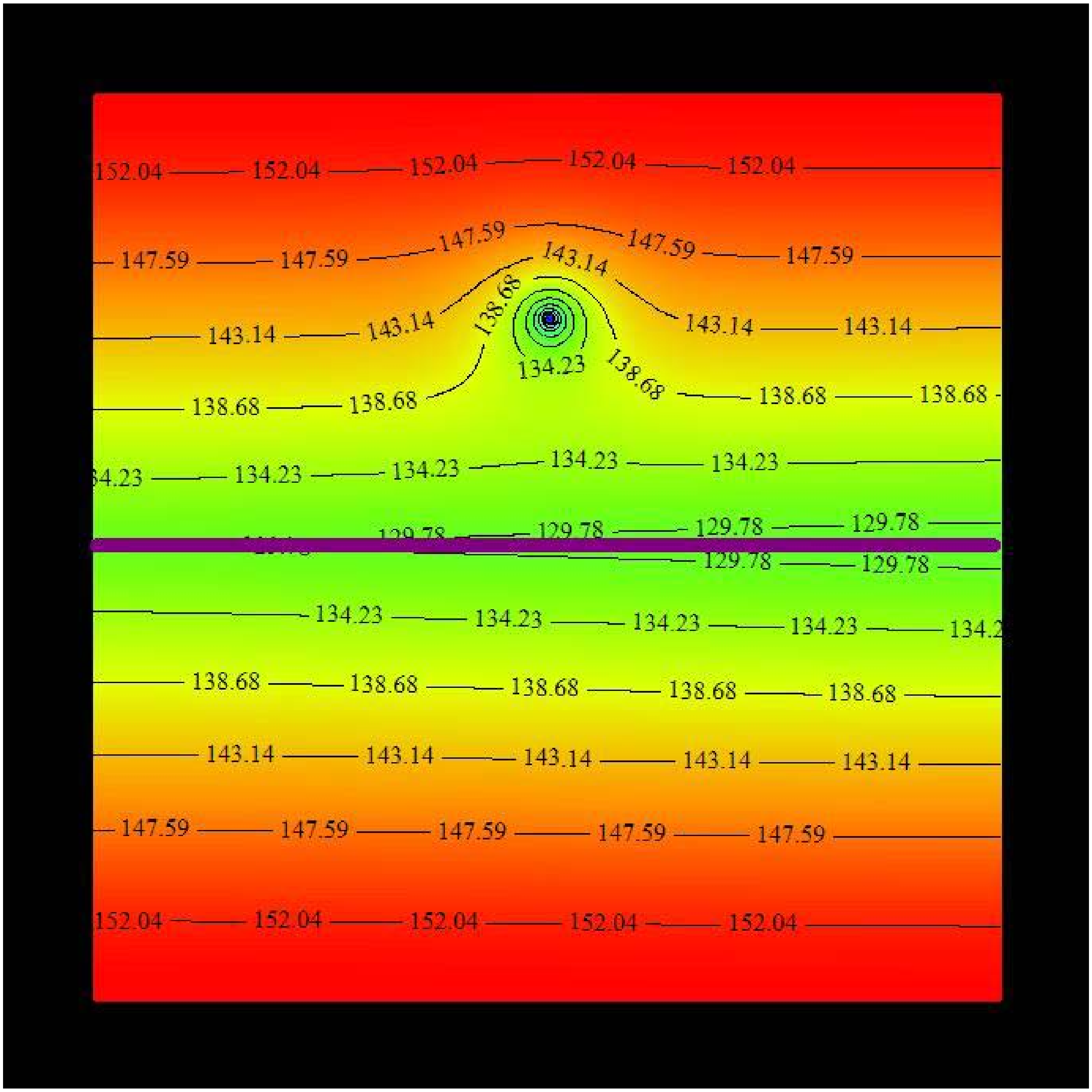


Figure 50. Result of transient state model run for CR 1 well with well pumping for 30 days with river and stream.

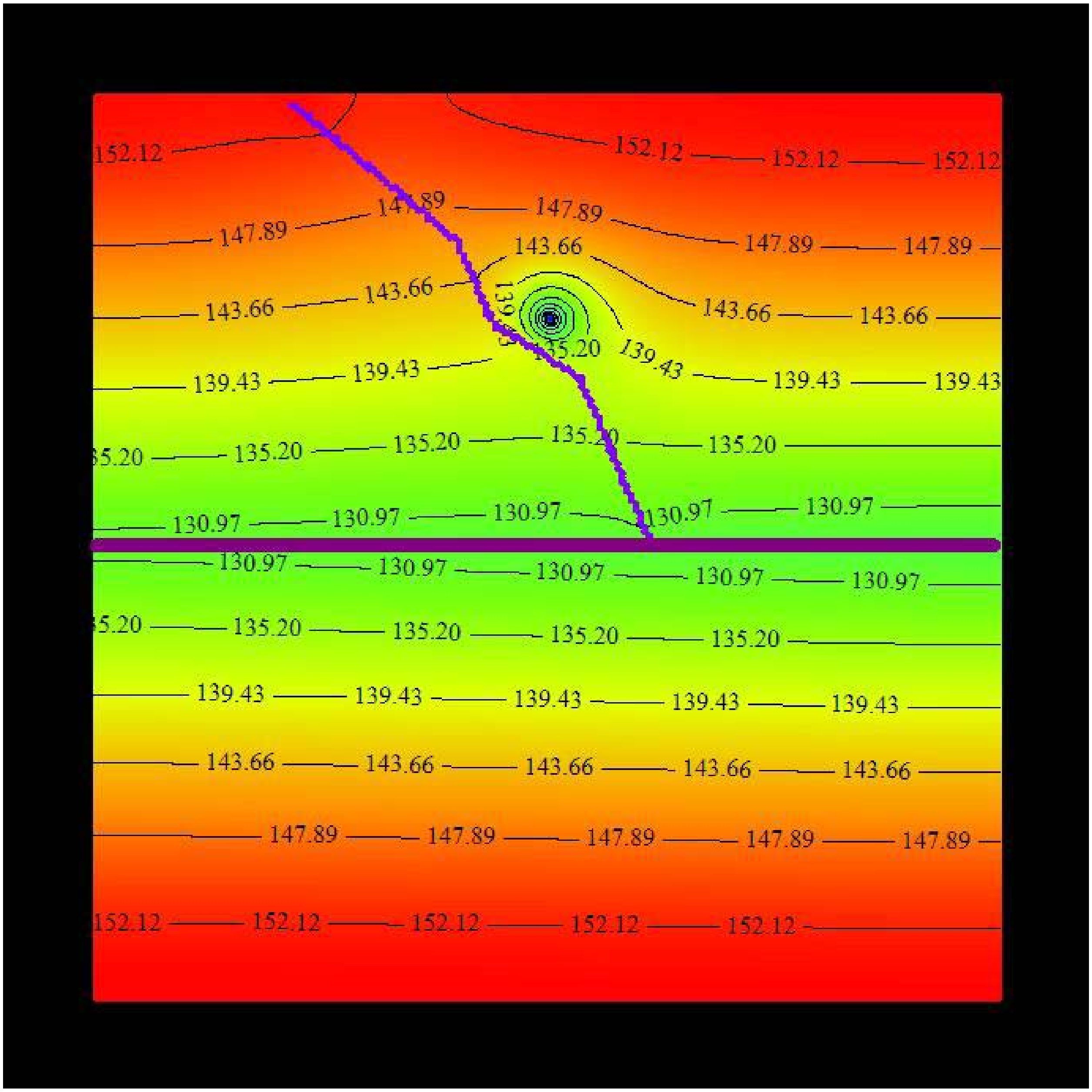


Figure 51. Result of transient state model run for CR 1 well with well pumping for 90 days with river only.

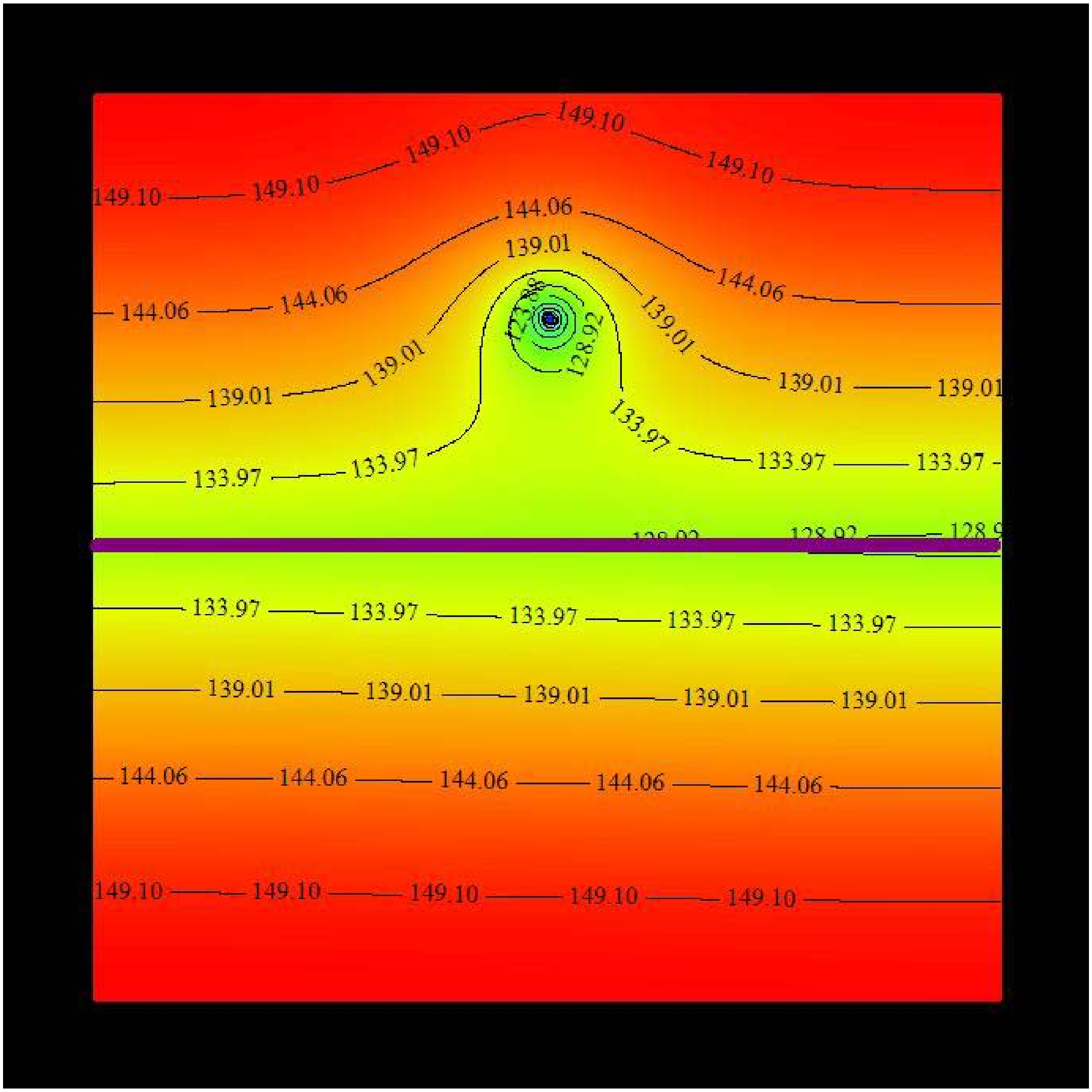


Figure 52. Result of transient state model run for CR 1 well with well pumping for 90 days with river and stream.

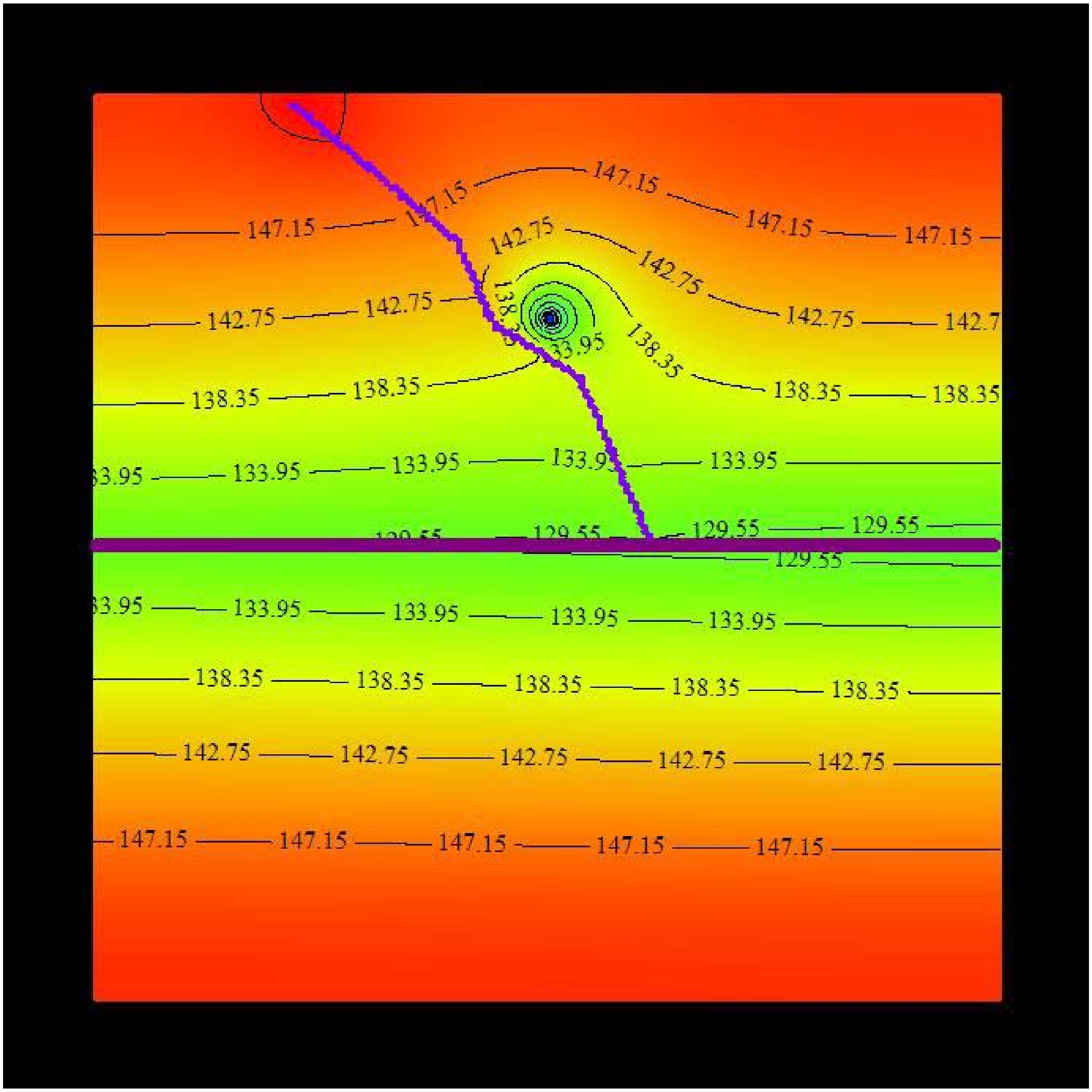


Figure 53. Result of transient state model run for CR 1 well with well pumping for 180 days with river only.

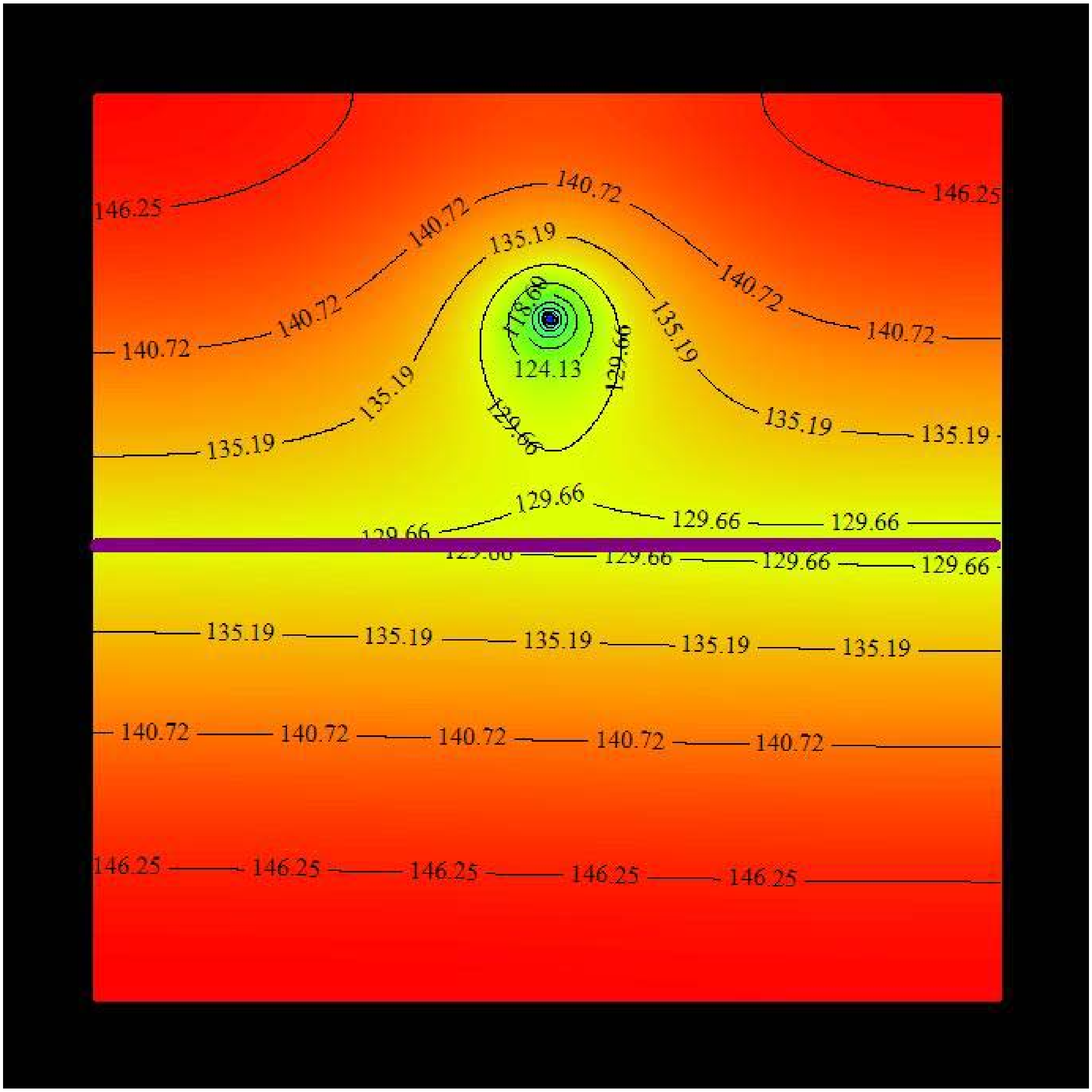


Figure 54. Result of transient state model run for CR 1 well with well pumping for 180 days with river and stream.

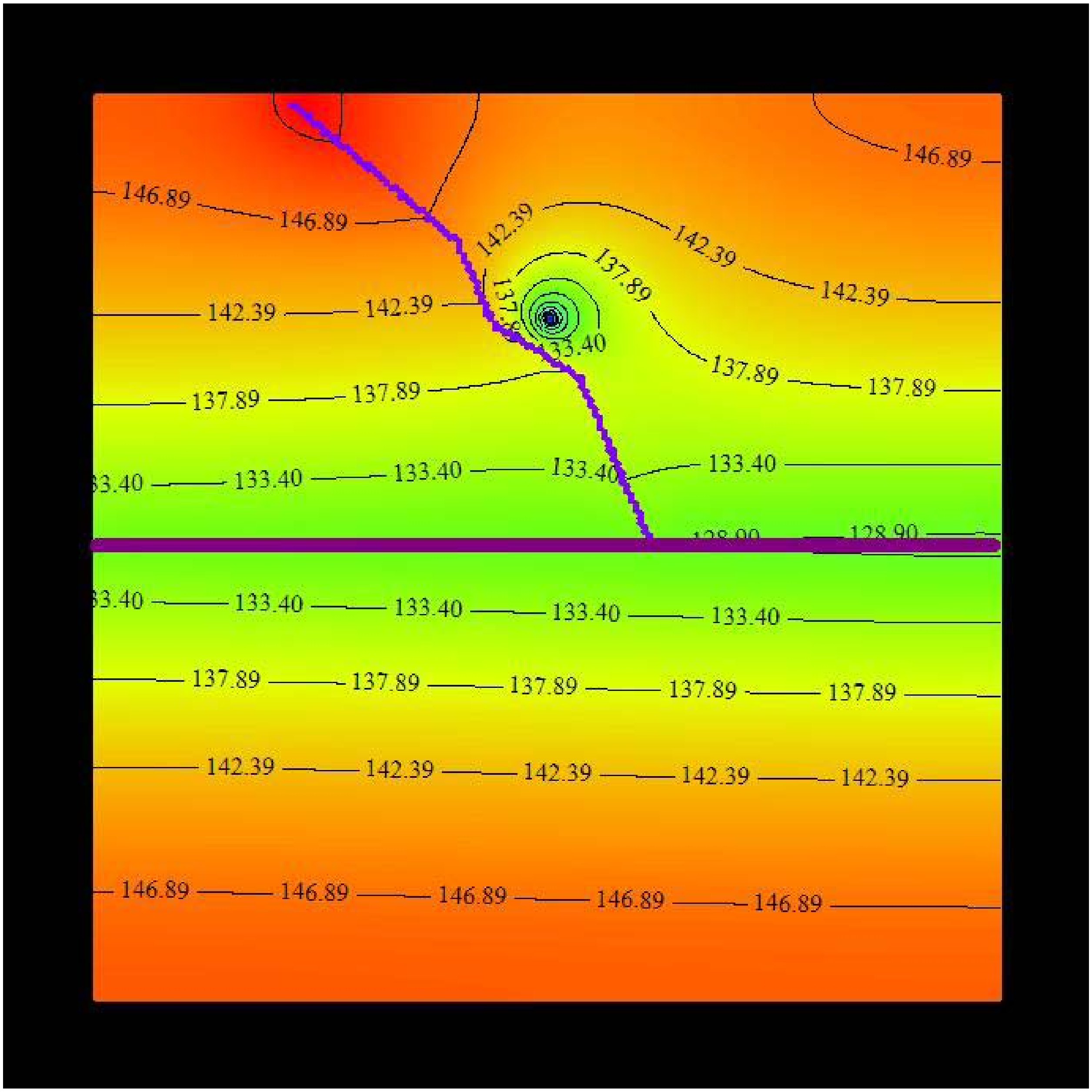


Figure 55. Result of transient state model run for CR 1 well with well pumping for one year with river only. Well has been pumped dry.

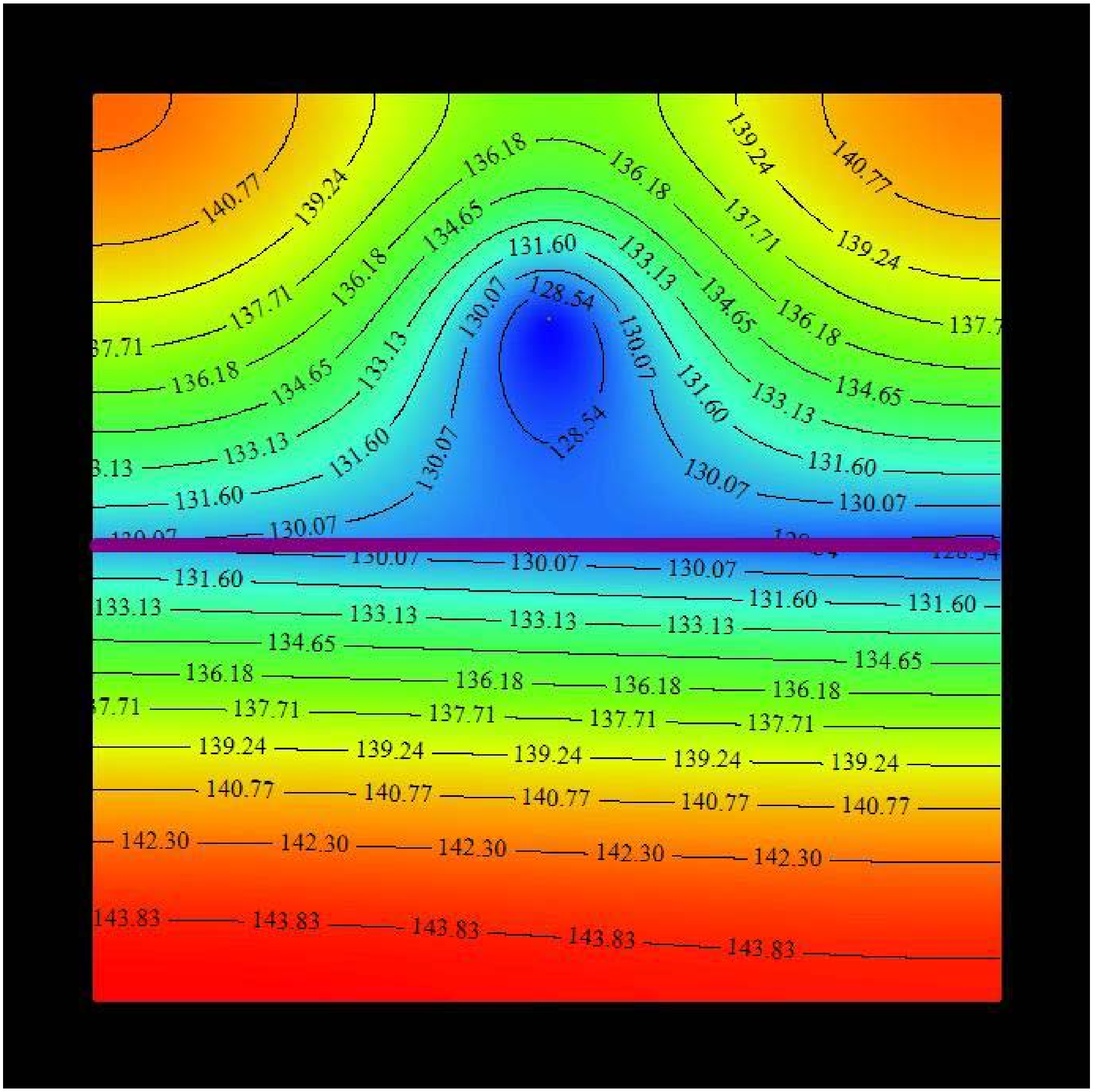


Figure 56. Result of transient state model run for CR 1 well with well pumping for one year with river and stream.

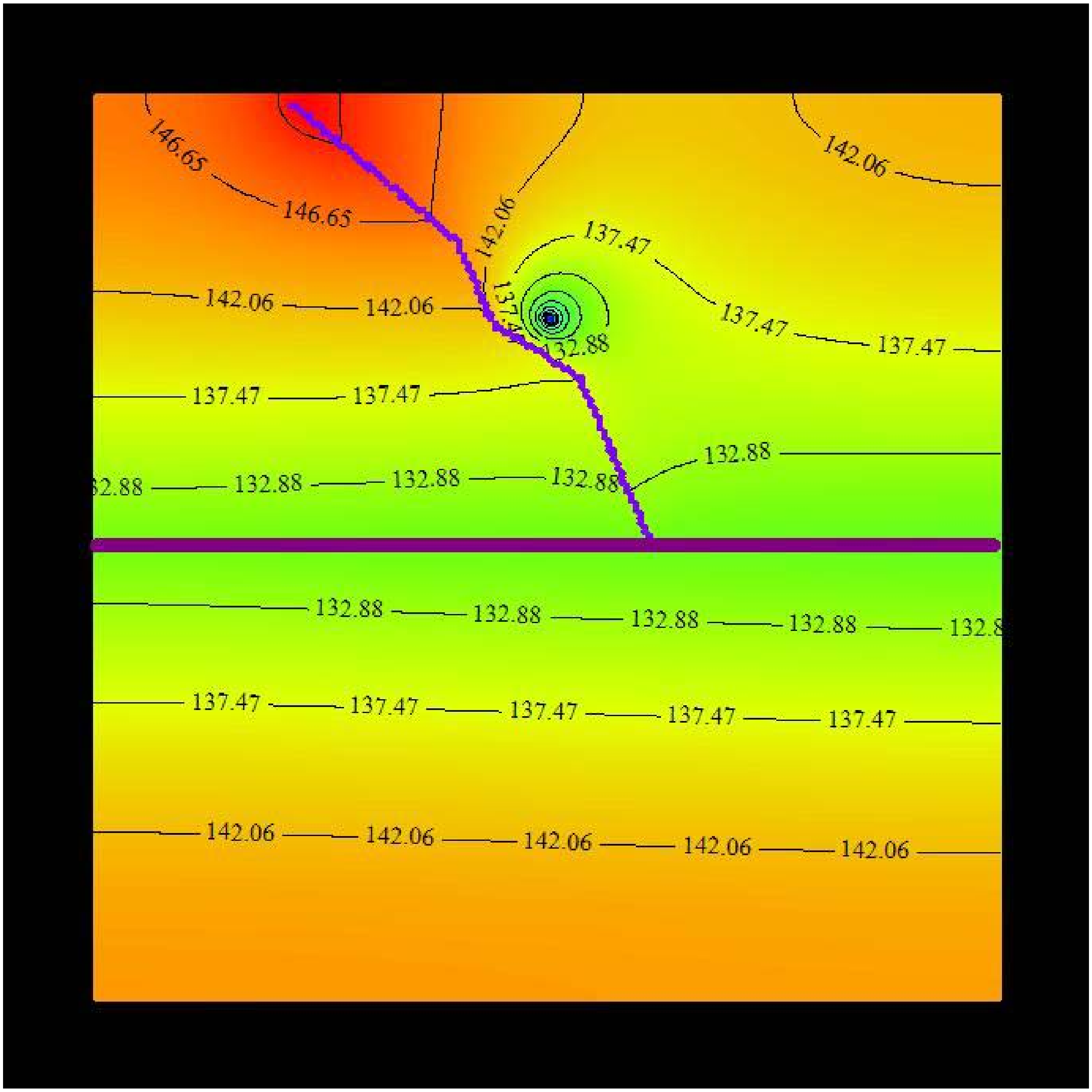


Figure 57. Result of transient state model run for CR 1 well with well pumping for five years with river only. The well has been pumped dry and shows no cone of depression.

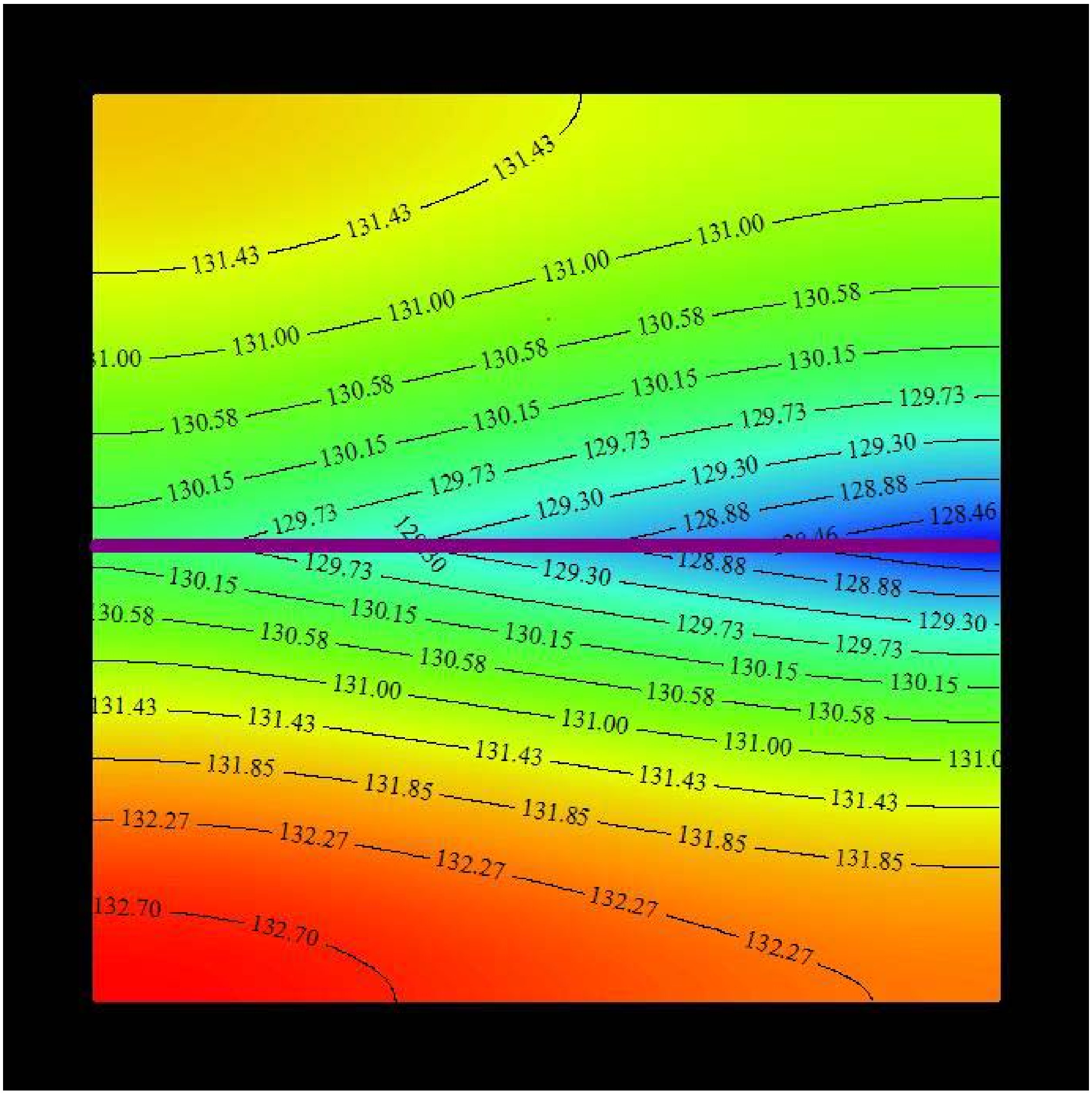


Figure 58. Result of transient state model run for CR 1 well with well pumping for five years with river and stream.

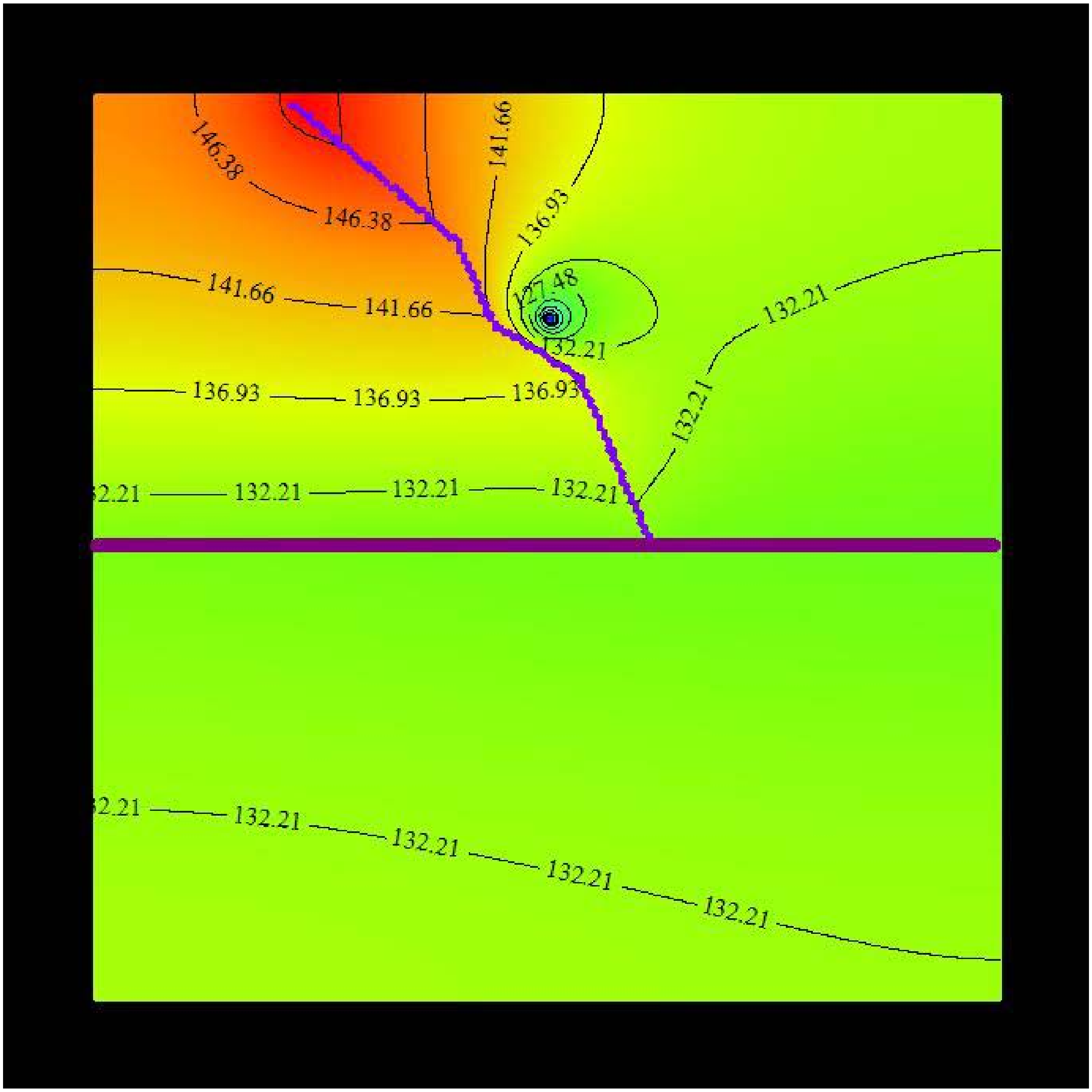


Figure 58 is a good example of how recharge rates or general head boundaries do not perform well in these models over longer run times. The cone of depression for CR 1 does not extend to the White River, thus there should be no decrease in head values over time. This observation indicates that the modeling results may create larger cones of depression than what would actually be present.

3. CR 2 WELL

Results from modeling well CR 2 can be seen in subsequent figures and head values are given in Table 27. Initially a modeling run was completed to determine if the White River would have any influence on the well. This yielded a model size of 6,800 feet by 6,800 with a 200 by 200 cell grid and 34 feet by 34 feet cells.

A river boundary was put in place on the left side of the model and a constant head boundary with an elevation of 309 feet was put in on the right side of the model. River boundary input data are in Table 34. The river attributes were defined in the creation of the boundary by defining values at the start and end point vertices and then the model used a linear interpolation of that data. The well was placed in the center of the model with a location of (3400, 3400). The model was calibrated to steady state. Transient state runs from the steady state model at one and five year intervals indicated that the river had no influence on the well and that a smaller cell size would yield more appropriate results. Also, at the one and five year timeframes the well was pumped dry. The low pump rate of 50 GPM for the well contributed to the limited influence on the aquifer by the well.

Table 34. River boundary input information for CR 2 model.

Location	Stage	Bottom	Thickness	Width	Riverbed K ft./day
Point 0	85	65	1	440	3
Point 1	84	64	1	440	3

A model with dimensions of 2,000 feet by 2,000 feet with 10 feet by 10 feet cells was developed as a second model run. This model dimension was more appropriate and yielded better results than the larger size. For this model, constant head boundaries were placed on the right and left sides of the model grid. The upgradient constant head boundary on the right side of the model was assigned a value of 230 feet. The downgradient constant head boundary on the left side of the model was assigned a value of 164 feet. The pumping well had coordinates of (1000, 1000).

Figure 59. Result of 6,800 feet by 6,800 feet steady state model of well CR 2 with constant head boundary and river boundary.

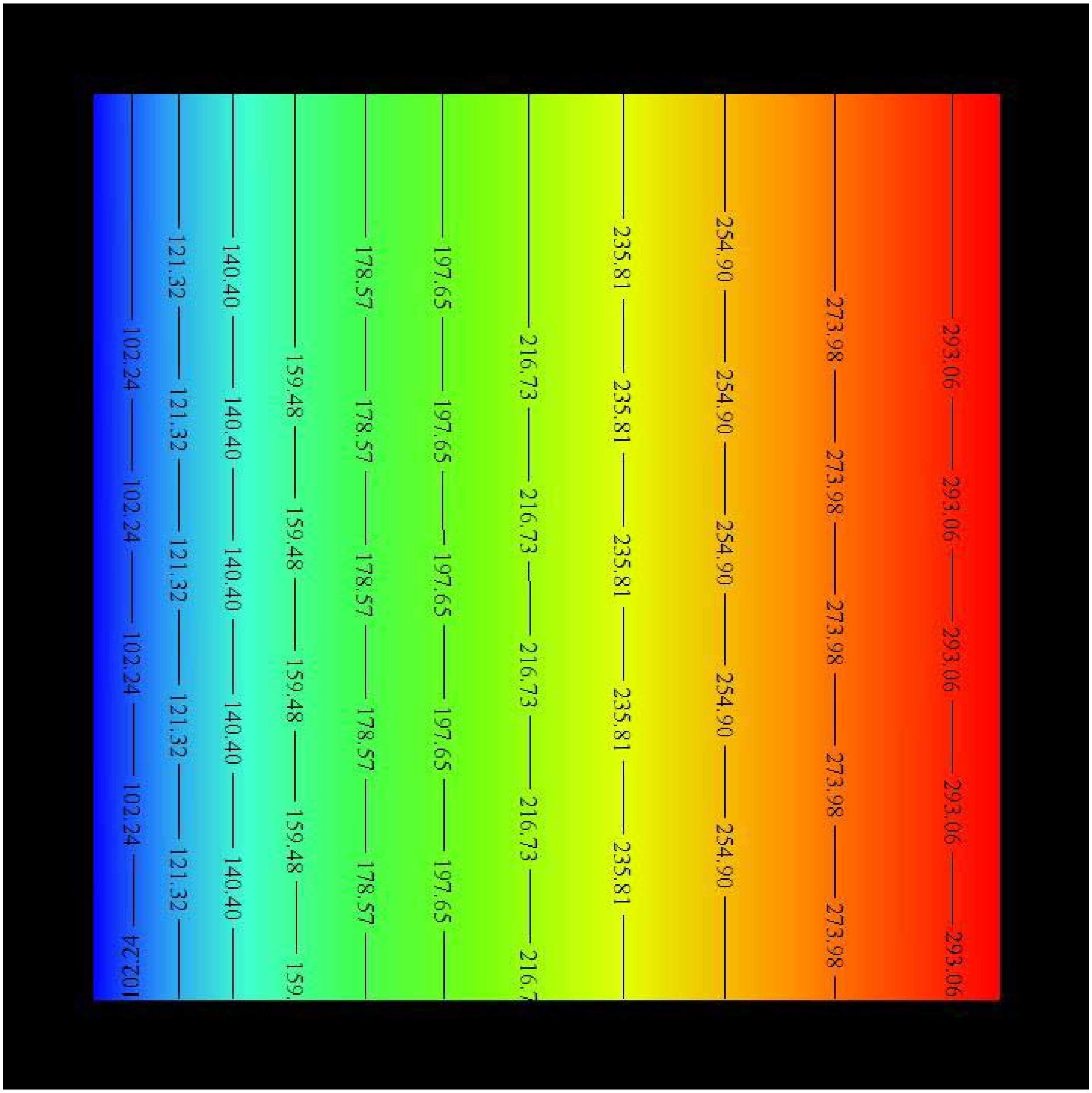


Figure 60. Result of 6,800 feet by 6,800 feet transient state model of well CR 2 with constant head boundary, river boundary, and well pumping for one year. Note that well is dry according to model.

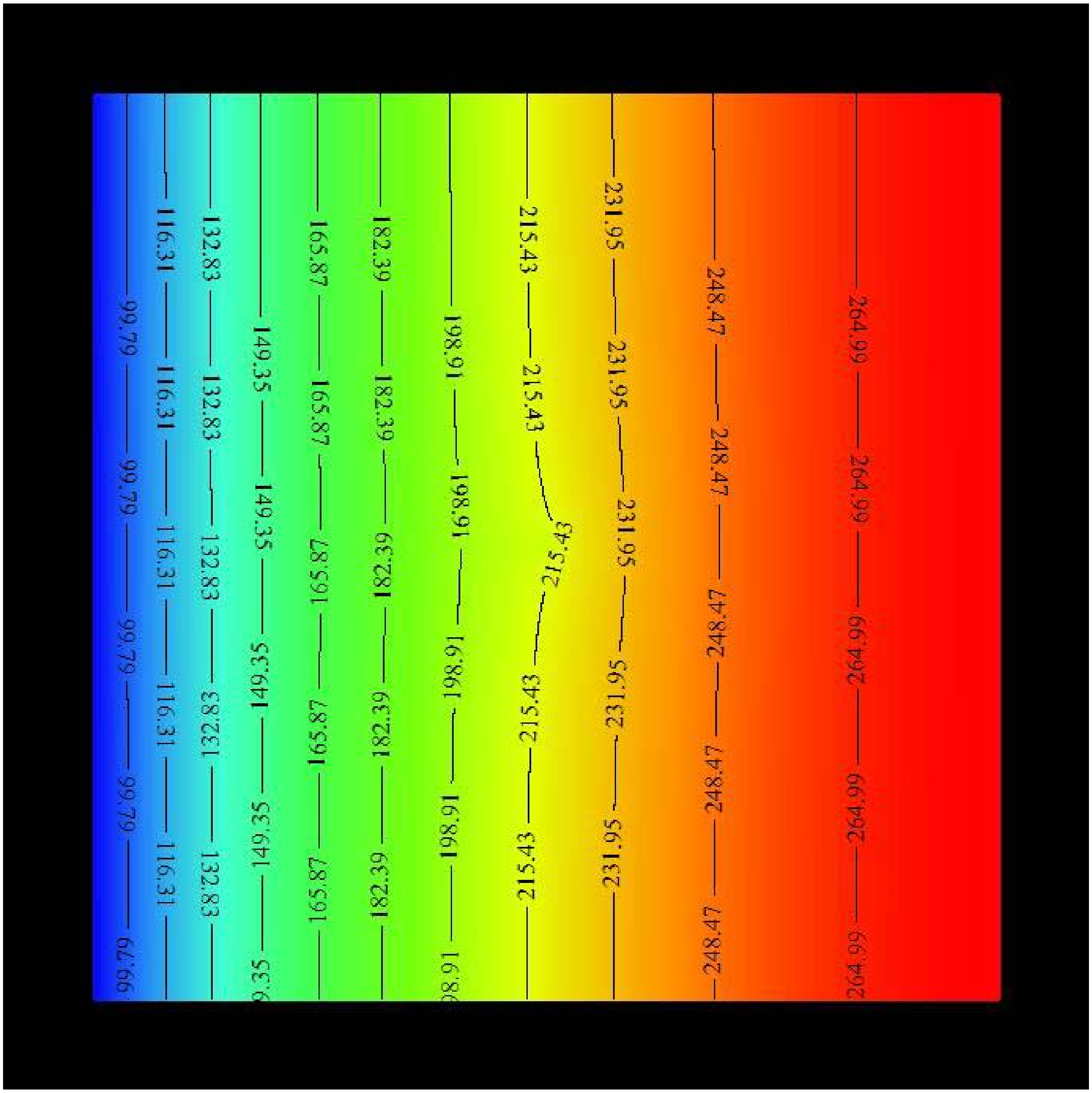


Figure 61. Result of 6,800 feet by 6,800 feet transient state model of well CR 2 with constant head boundary, river boundary, and well pumping for five years. Well is dry according to model.

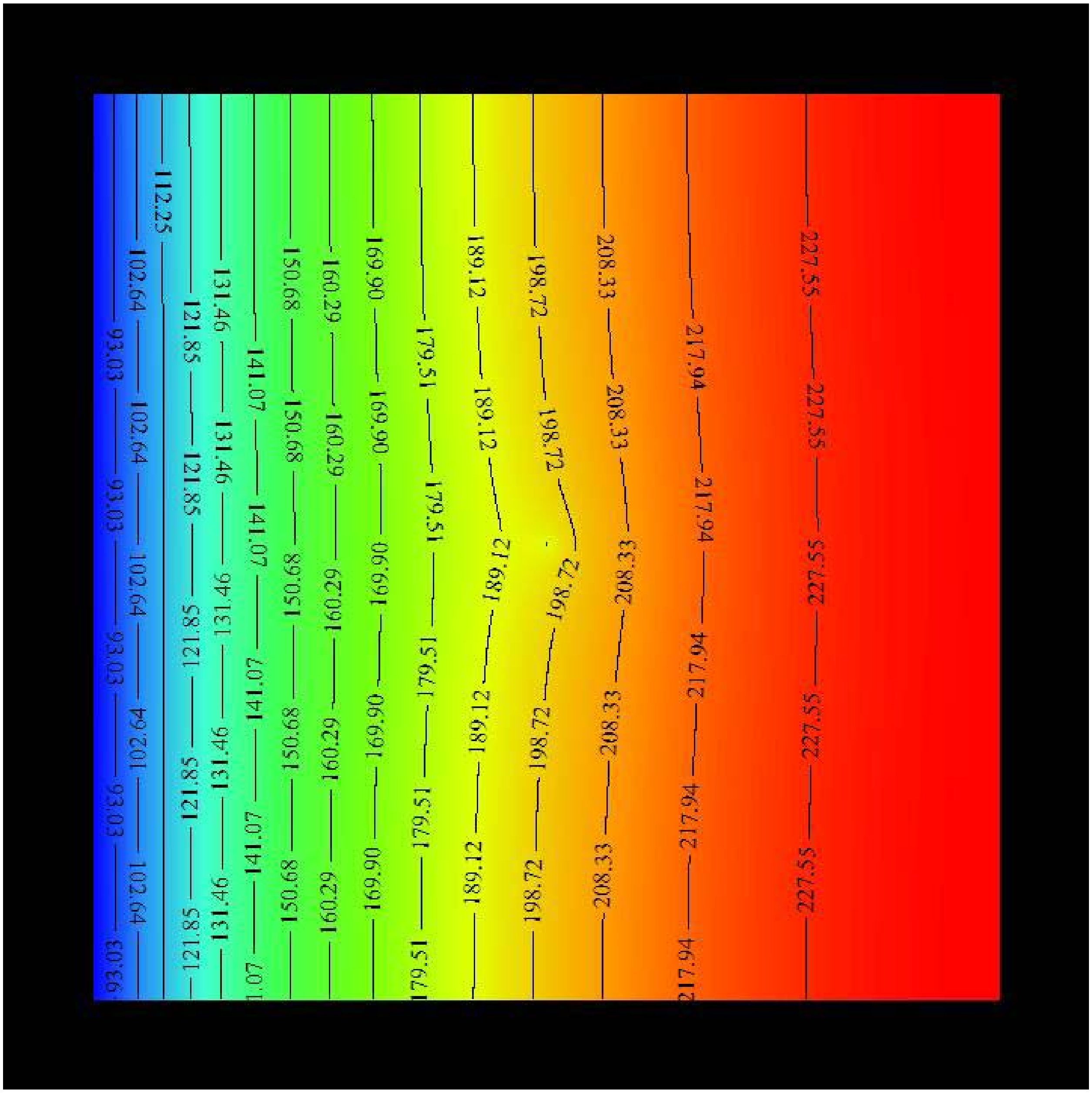


Figure 62. Result of 2,000 feet by 2,000 feet steady state model run for CR 2 well.

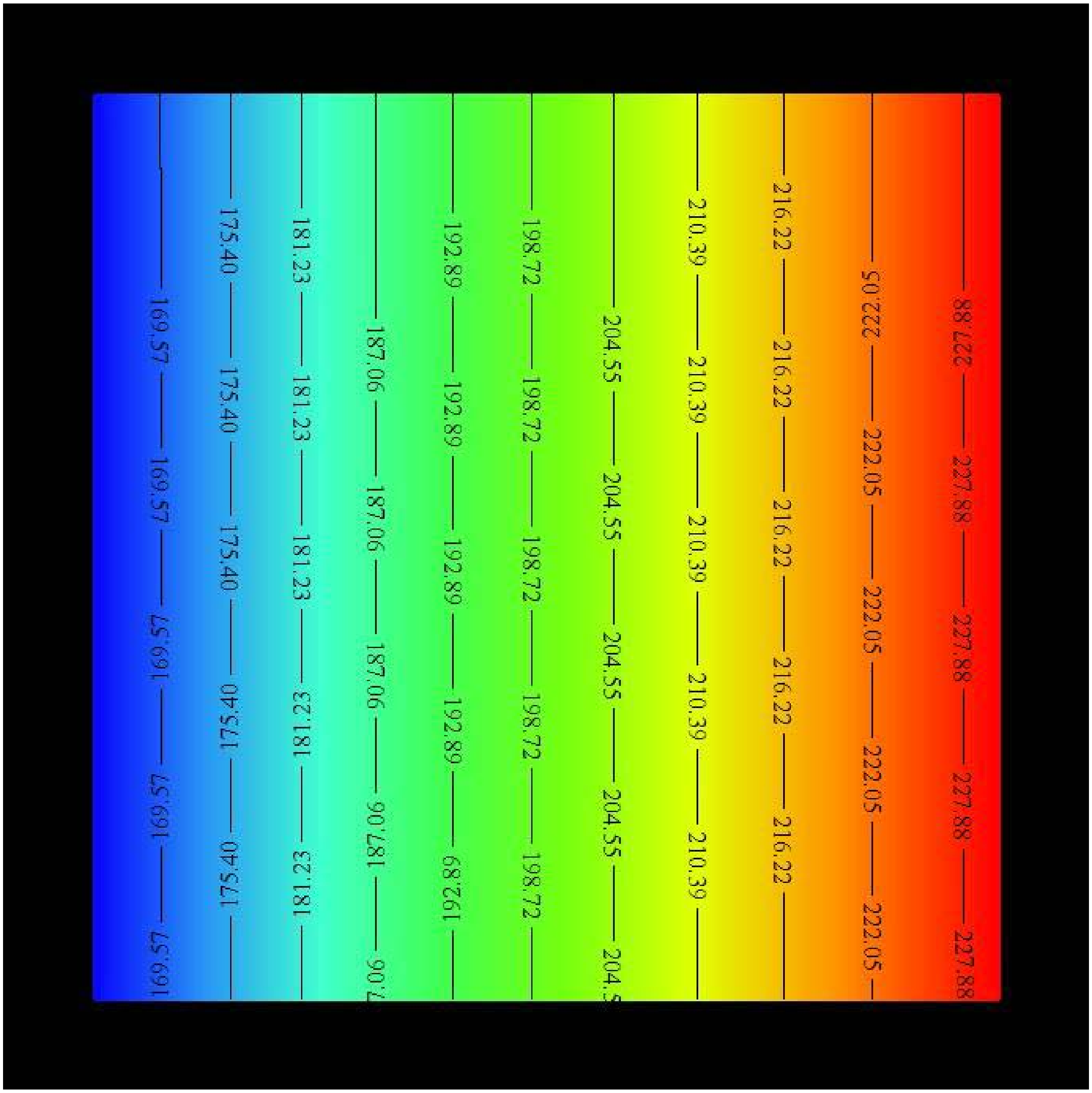


Figure 63. Result of 2,000 feet by 2,000 feet transient state model run for CR 2 well with well pumping for one day.

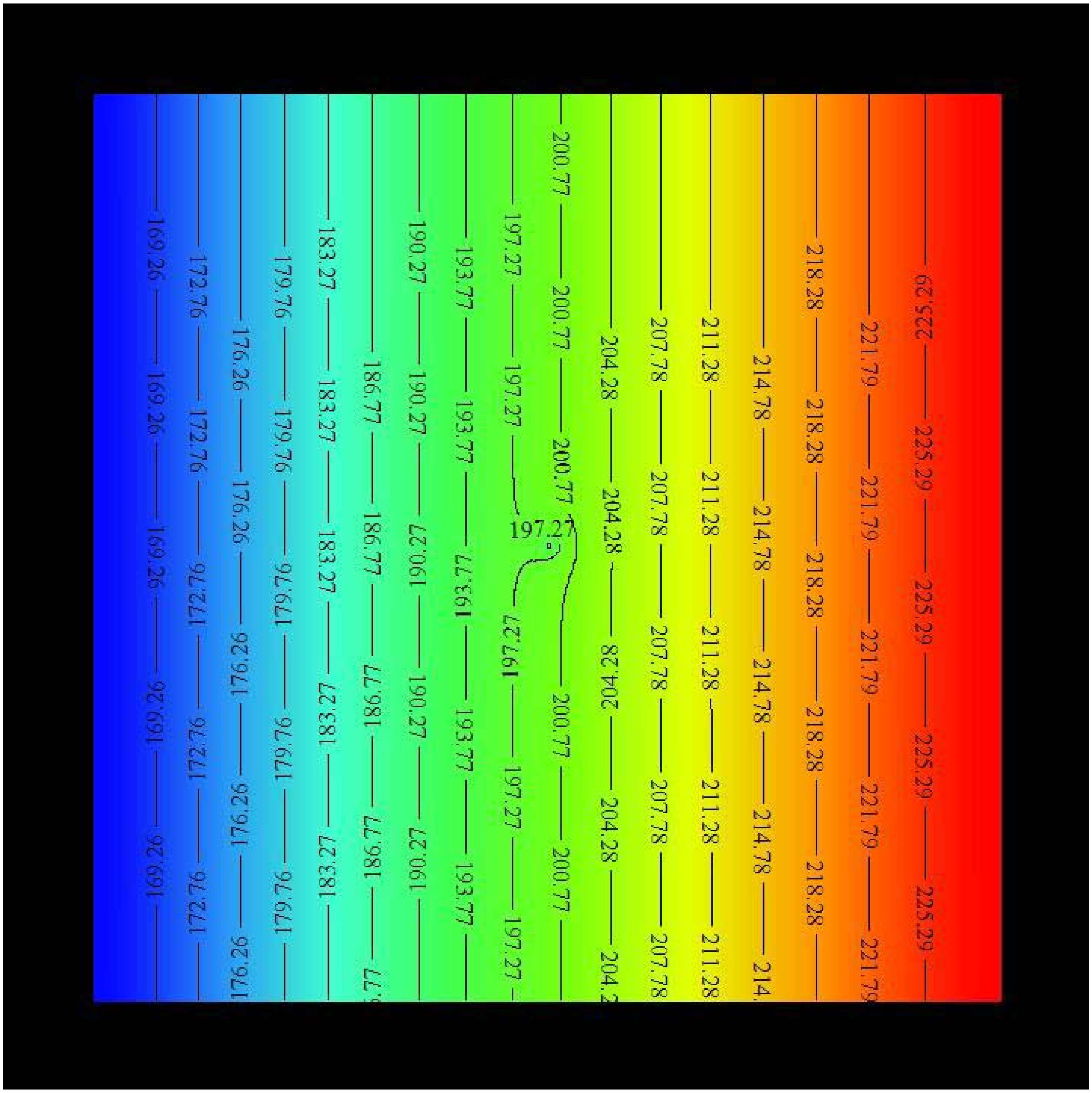


Figure 64. Result of 2,000 feet by 2,000 feet transient state model run for CR 2 well with well pumping for 30 days.

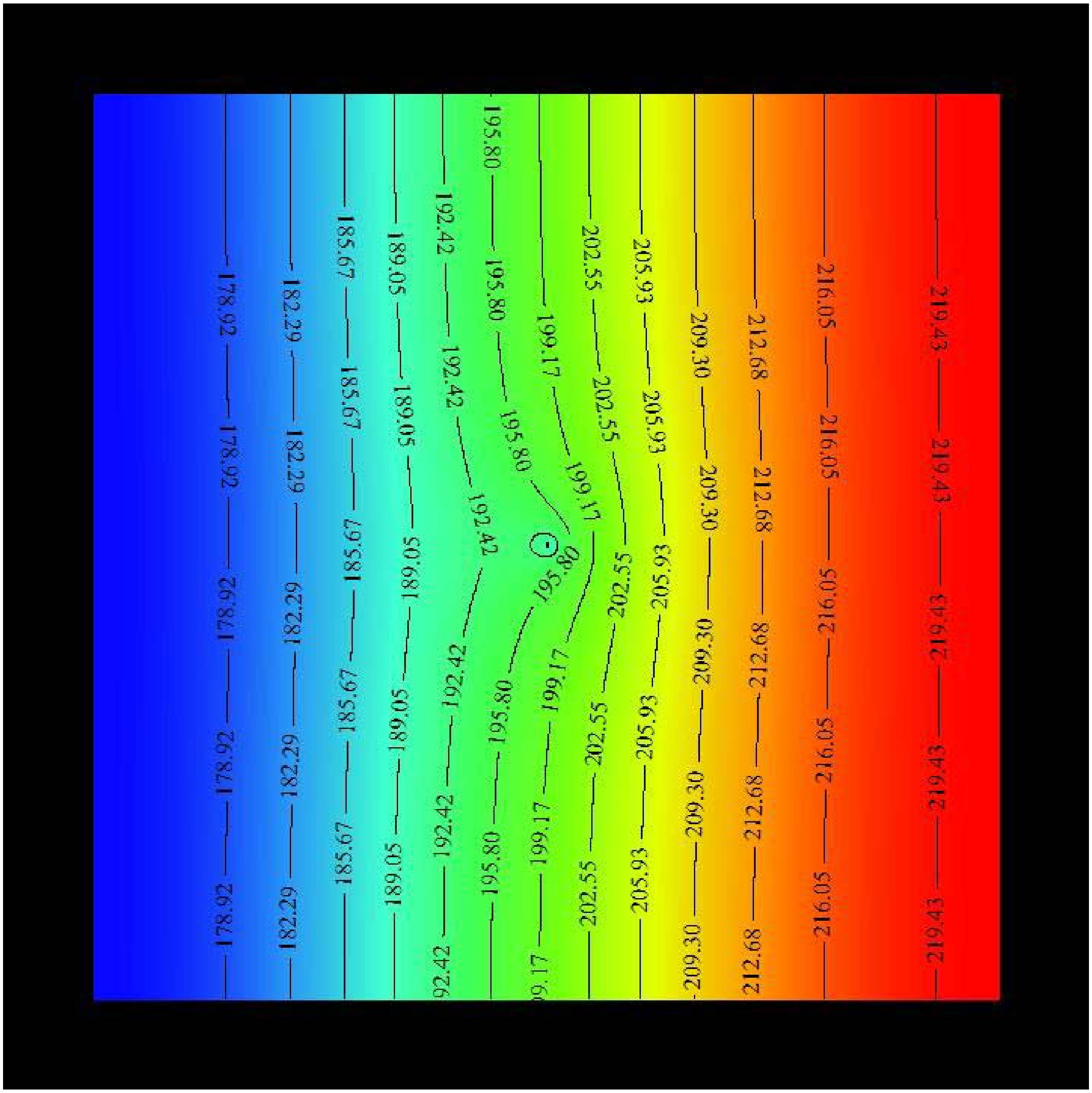


Figure 65. Result of 2,000 feet by 2,000 feet transient state model run for CR 2 well with well pumping for 90 days.

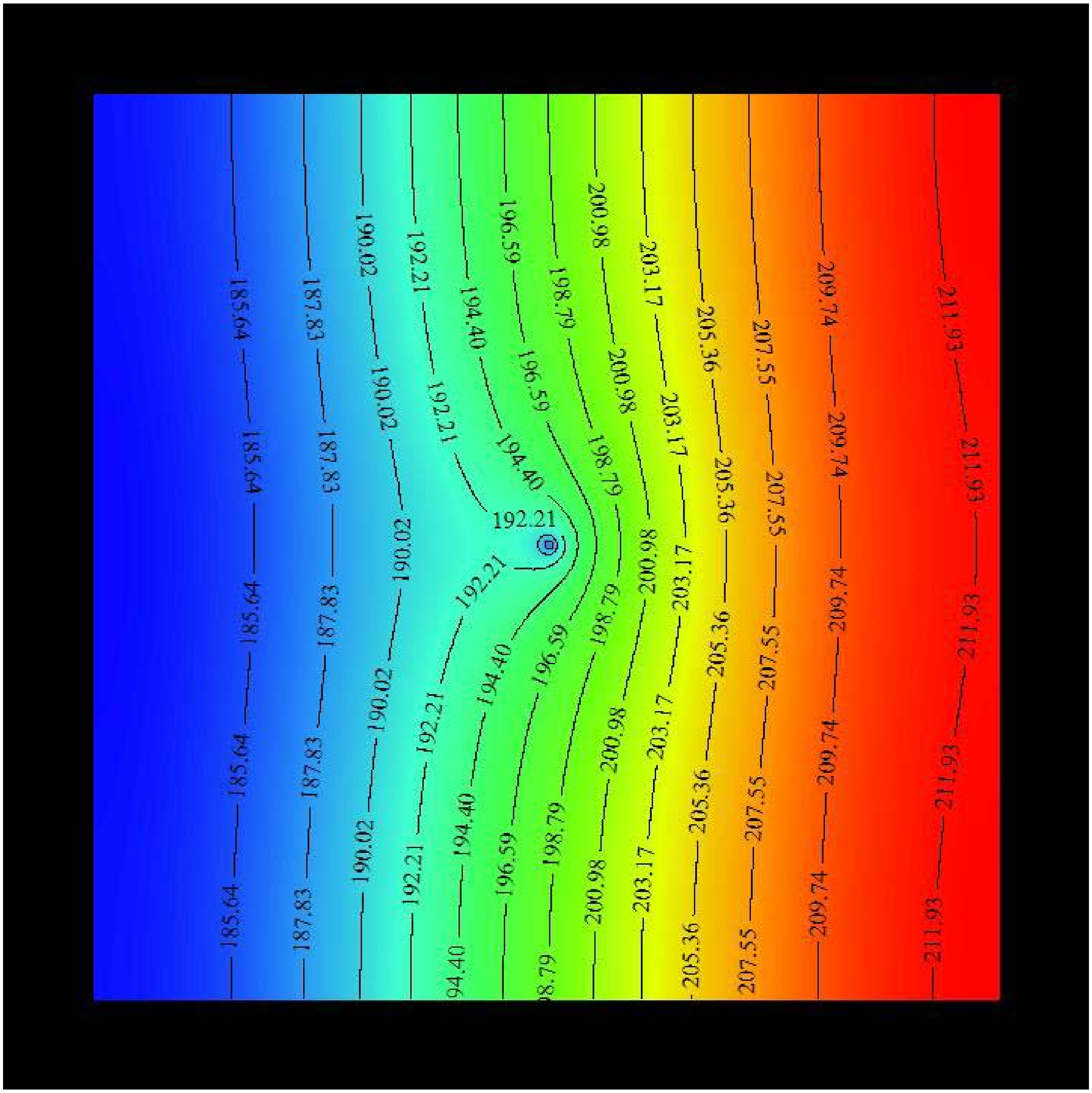


Figure 66. Result of 2,000 feet by 2,000 feet transient state model run for CR 2 well with well pumping for 180 days.

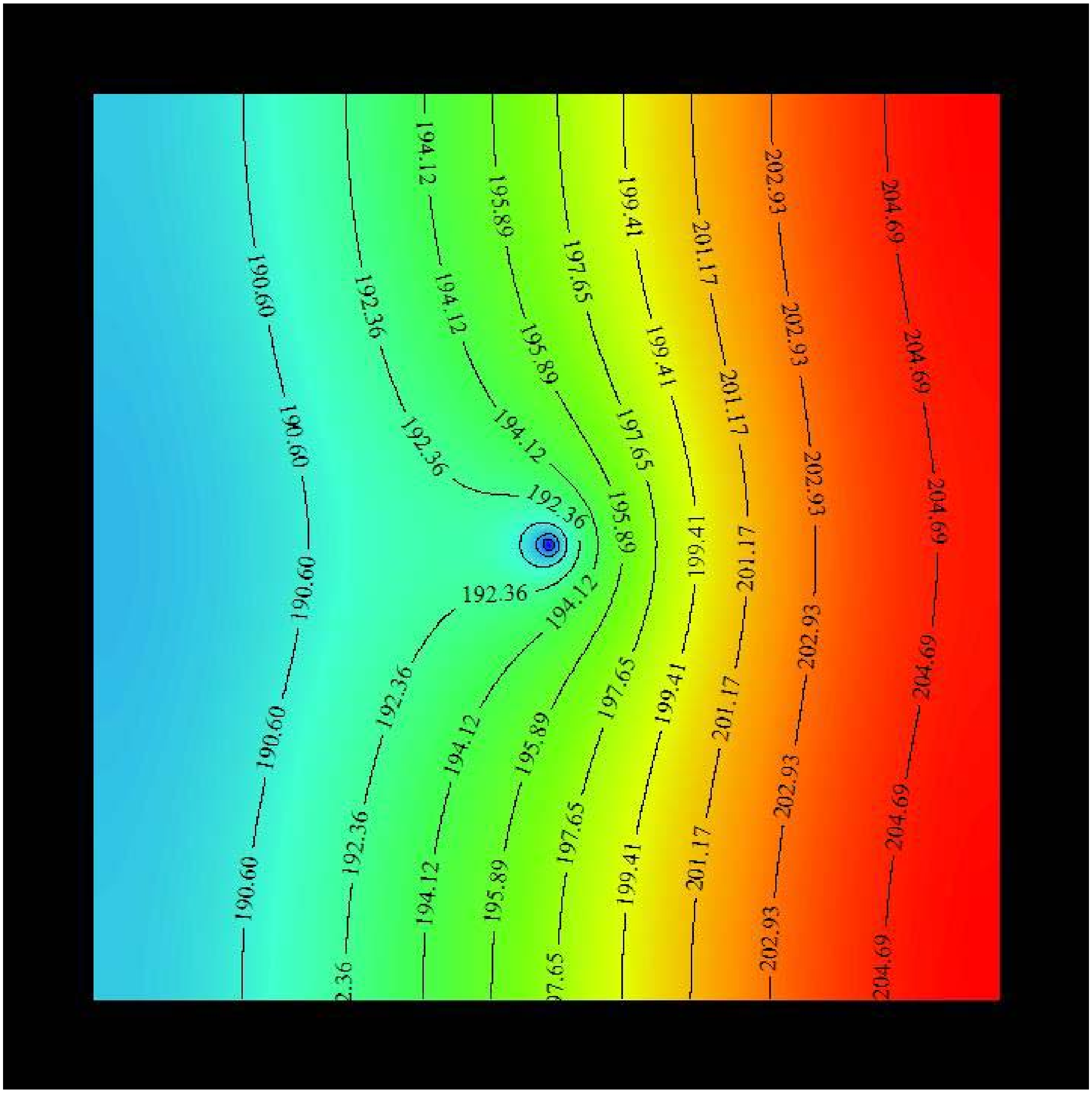


Figure 67. Result of 2,000 feet by 2,000 feet transient state model run for CR 2 well with well pumping for one year.

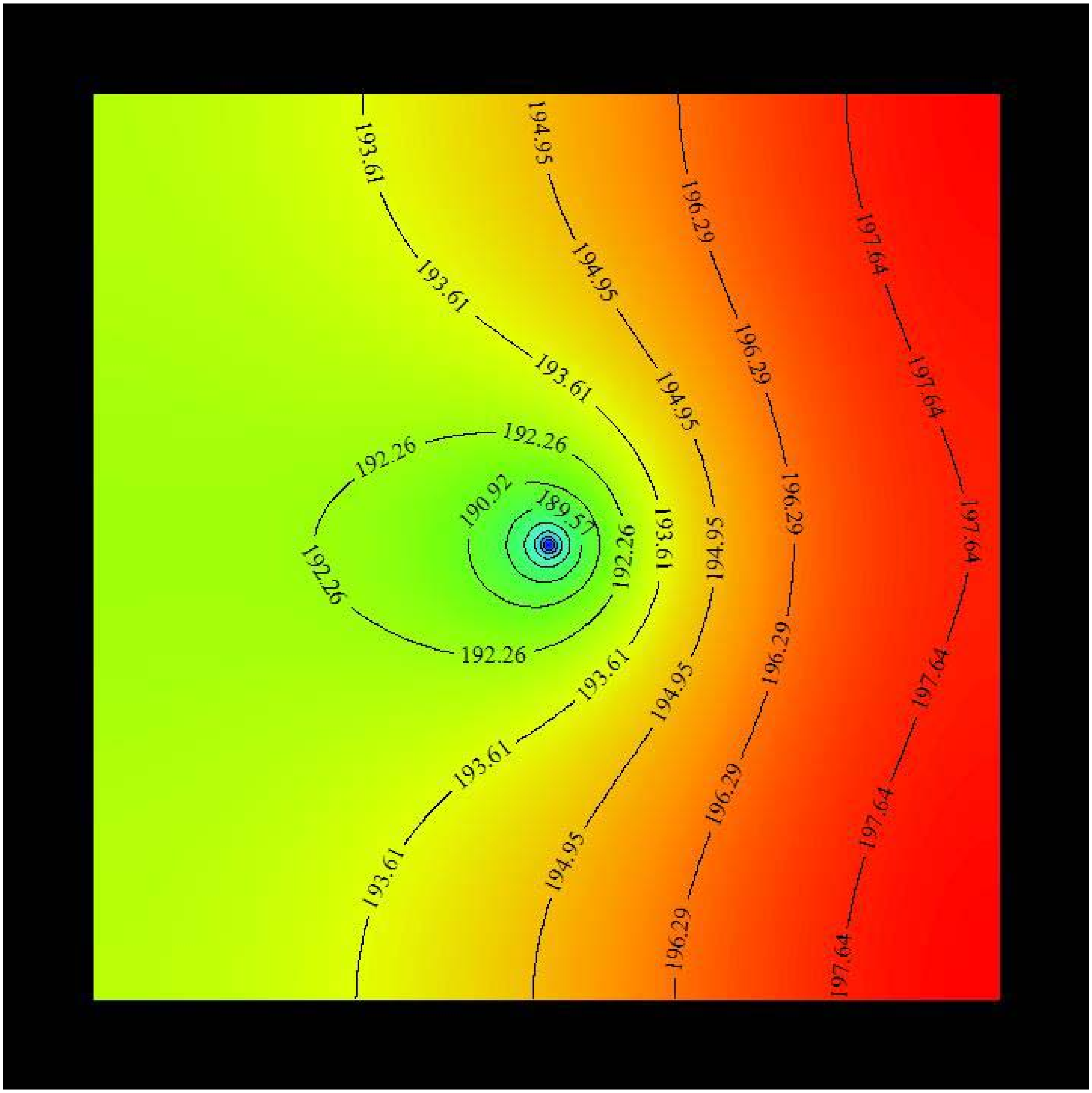
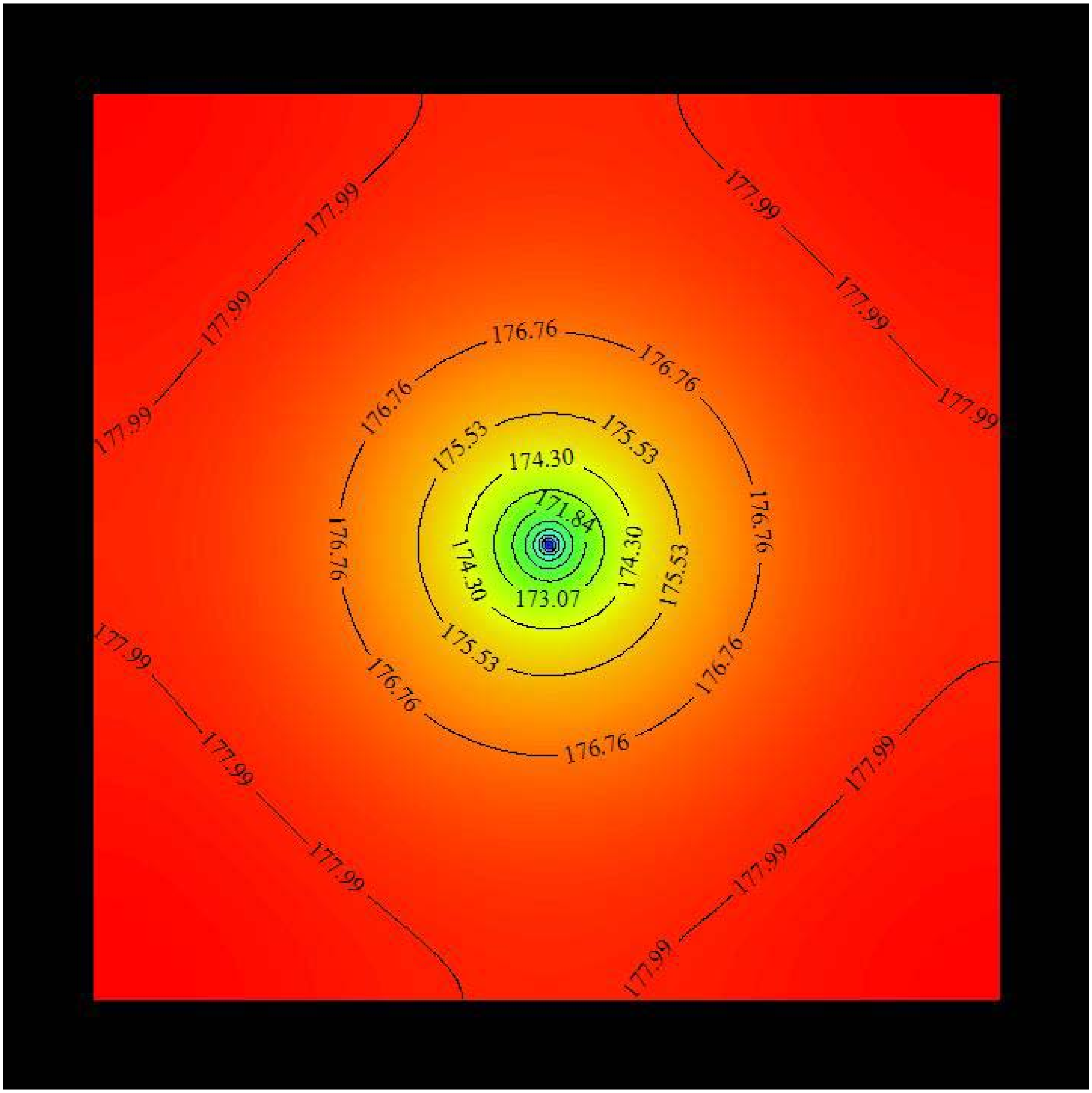


Figure 68. Result of 2,000 feet by 2,000 feet transient state model run for CR 2 well with well pumping for five years.

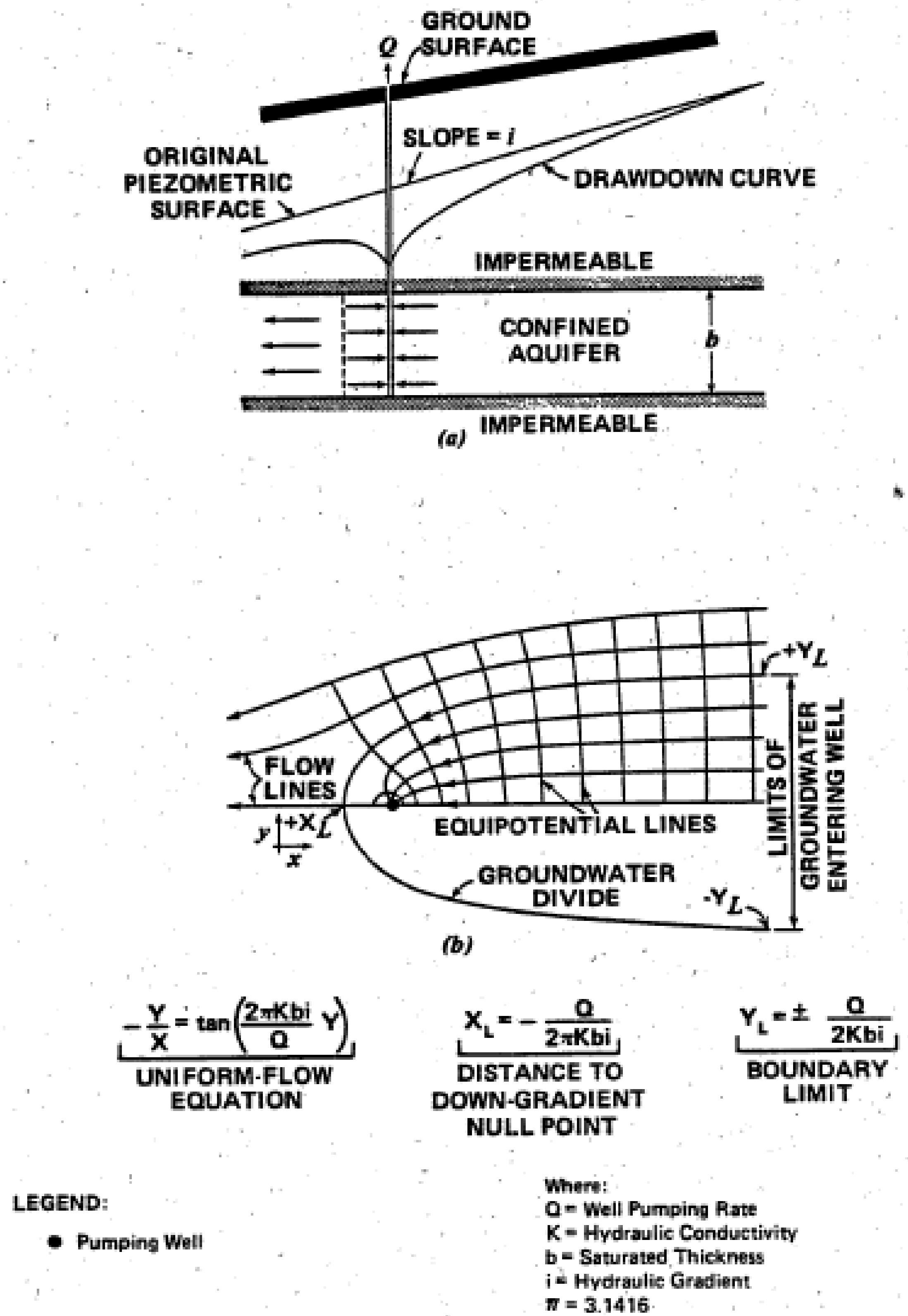


C. ANALYTICAL MODEL COMPARISON

1. CAPTURE ZONE ANALYSIS

Figure 69 shows the Uniform Flow Analytical Model with equations and definitions for terms used for calculating well capture zones. Values utilized in the MODFLOW modeling were input into the formulas to solve for X_L and total Y_L where Total $Y_=(2^* +Y_L)$. MODFLOW modeling results were then examined and X_L was determined for the 30 day modeling time and the five year. Only HI 1 and CR 1 MODFLOW models reached steady state by five years due to the influence of surface water bodies. The HI 2 21,120 feet by 21,120 feet model indicated a X_L of 4,224 feet but this model size may yield inaccurate results. Where steady state conditions were not reached the MODFLOW modeling results were given as the dimension of the model. Table 35 includes the results of the calculations and analysis of MODFLOW model results. Results of the comparison are grouped into two separate bar graphs in Figures 70 and 71, as wells HI 2, HI 4, and HI 5 had much larger resulting values than the other wells.

Figure 69. Wellhead protection area delineation using the Uniform Flow Analytical Model (EPA 1987)



$$-\frac{Y}{X} = \tan\left(\frac{2\pi Kbi}{Q} Y\right) \qquad X_L = -\frac{Q}{2\pi Kbi} \qquad Y_L = \pm \frac{Q}{2Kbi}$$

Table 35. Data used for input and results of the calculations using Uniform Flow Analytical Model (Calculated numbers) and analysis of MODFLOW model results.

Well ID	Well Yield ft^3/ day	Aquifer Thick- ness ft.	Hydrau- lic Gradient	K ft./ day	Y Total Calculated ft.	X_L Calculated ft.	X_L Model ft.	X_L Model 30 Days ft.
HI 1	96250	991	0.0355	3	912	145	1050	216
HI 2	96250	1037	0.0019	3	16283	2592	4224	1480
HI 4	96250	1360	0.0019	3	12416	1976	4000	1224
HI 5	96250	1038	0.0019	3	16268	2589	4000	1306
CR 1	28875	140	0.0135	3	5093	811	125	125
CR 2	9625	300	0.0329	3	325	52	2000	82
CR 4	7700	570	0.0095	0.3	4740	754	4000	326
CR 5	9625	1674	0.0095	0.3	2017	321	4000	408
CR 6	28875	1880	0.0095	0.3	5389	858	4000	816

Figure 70. Bar graph comparing Uniform Flow Analytical Model (Calculated numbers) results and analysis of MODFLOW model results for HI 2, HI 4, and HI 5.

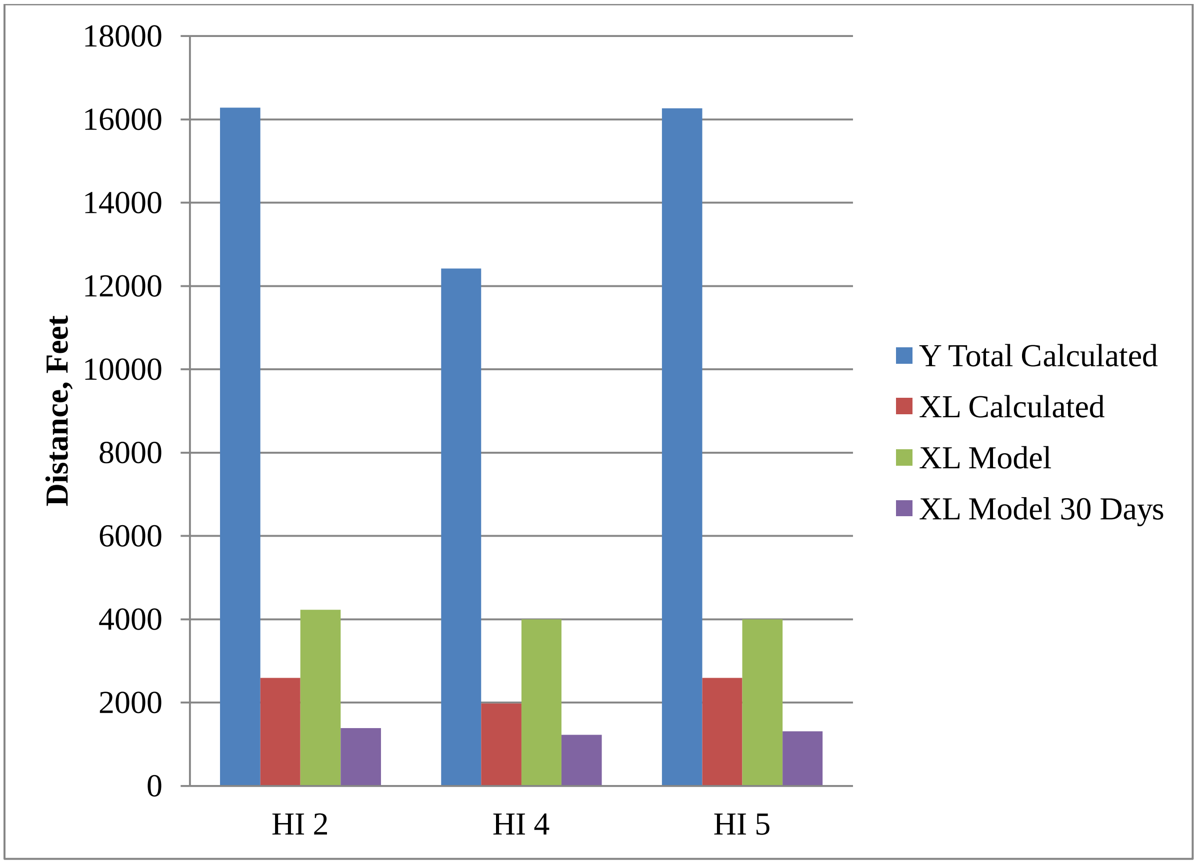
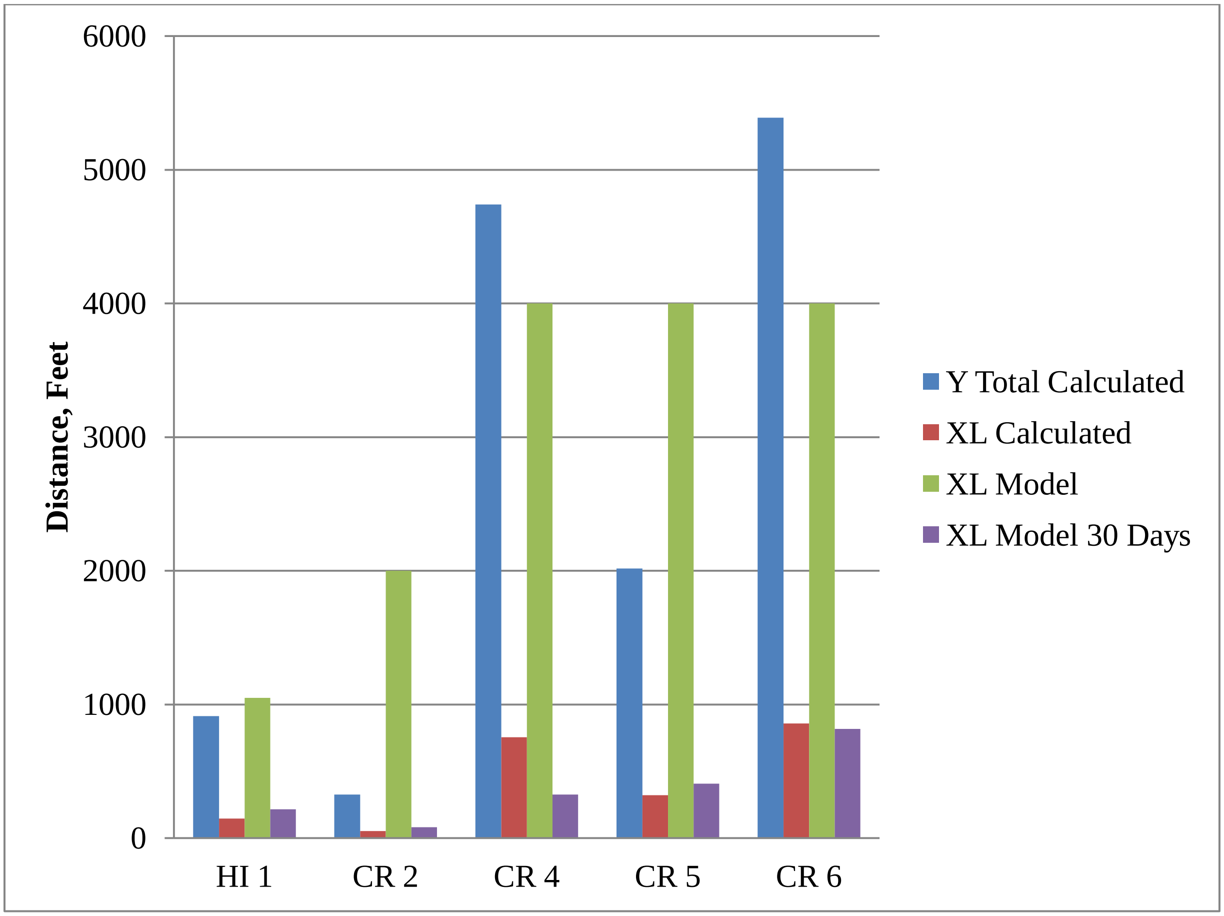


Figure 71 . Bar graph comparing Uniform Flow Analytical Model (Calculated numbers) results and analysis of MODFLOW model results for HI 1, CR 2, CR 4, CR 5, and CR 6.



2. THEIS EQUATION

As previously mentioned, the ADH reports written by Cordova utilize the Theis equation for calculating capture zones. Cordova varied the drawdown at boundary of WHPA area and time since pumping started for the radius calculations. For comparison, a drawdown equal to one foot at the edge of influence and a time period of 0.125 days was utilized for calculating radii from the values used in the MODFLOW models. Cordova had determined that well CR 1 was a GWUDI well and as the watershed for this well encompassed wells CR 2, and CR 4 he did not calculate radii for them. For comparison purposes, radii were calculated for the wells using aquifer values provided by Cordova in his report. A radius of 1,500 feet was calculated for CR 1, 1,000 feet for CR 2, and 900 feet for CR 4.

Table 36 lists values used for input into the Theis equation that were utilized in the MODFLOW models. Table 37 gives the radii results from using the Theis equation, MODFLOW model results for X_L for 30 days, values that Cordova calculated, and current protection radii that ADH uses. Y values for the width of the capture zone could not be determined for the 30 day pumping length in some of the MODFLOW models because they were larger than the modeling dimensions. Y values are estimated from the model results or are listed as a greater than value where they exceed the model dimension in Table 37. Figure 72 is a bar graph displaying the results for comparison purposes. Figure 73 utilizes the result from the HI 2 MODFLOW model for 30 days of pumping and includes radius and capture zone information from different results.

Table 36. Values used for input into Theis equation from MODFLOW model inputs.

Well ID	Well Yield ft.^{3}/day	Aquifer Thickness	K ft./day	T ft^2/day	S	Pumping Time Days	W (u)	u
HI 1	96250	991	3	2973	0.0001	0.125	0.38815	0.7
HI 2	96250	1037	3	3111	0.0001	0.125	0.40617	0.65
HI 4	96250	1360	3	4080	0.0001	0.125	0.53268	0.5
HI 5	96250	1038	3	3114	0.0001	0.125	0.40656	0.65
CR 1	28875	140	3	420	0.0001	0.125	0.18278	1.5
CR 2	9625	300	3	900	0.0001	0.125	1.17504	0.25
CR 4	7700	570	0.3	171	0.0001	0.125	0.27907	0.9
CR 5	9625	1674	0.3	502.2	0.0001	0.125	0.65567	0.45
CR 6	28875	1880	0.3	564	0.0001	0.125	0.24545	0.95

Table 37. Radii results in feet from Theis equation using MODFLOW values, MODFLOW model results for X_L for 30 days, Theis equation values that Cordova calculated, and current protection radii that ADH uses.

Well ID	MODFLOW Values	Cordova	ADH Current	X_L Model 30 Days	Estimated Y Model 30 Days
HI 1	3226	2000	100	216	415
HI 2	3180	2500	100	1480	>2000
HI 4	3194	2500	100	1224	>2000
HI 5	3181	2800	100	1306	>2000
CR 1	1775	1500	25	125	515
CR 2	1061	1000	50	82	350
CR 4	877	900	50	326	1000
CR 5	1063	1000	40	408	1000
CR 6	1637	3100	100	816	>2000

Figure 72. Bar graph displaying results listed in Table 37.

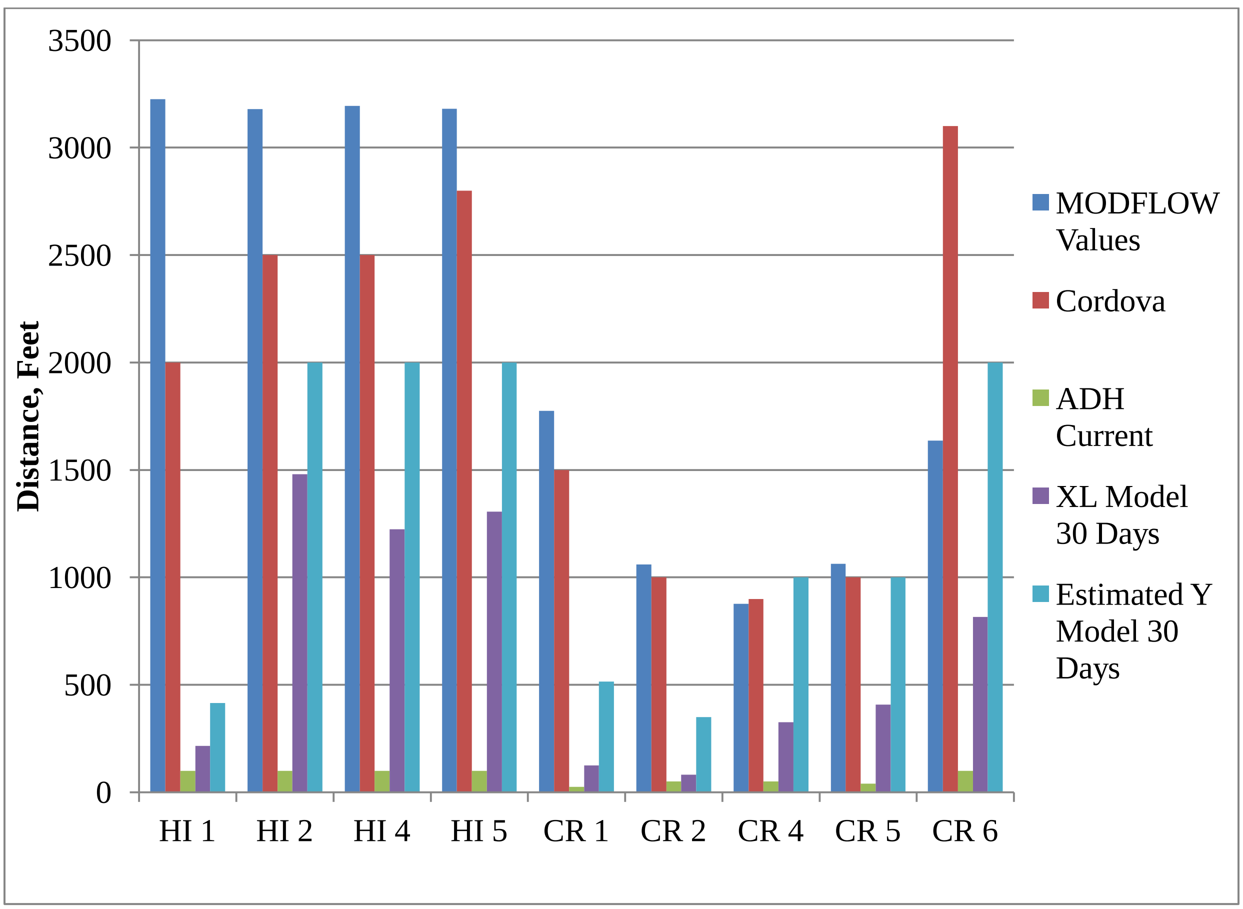
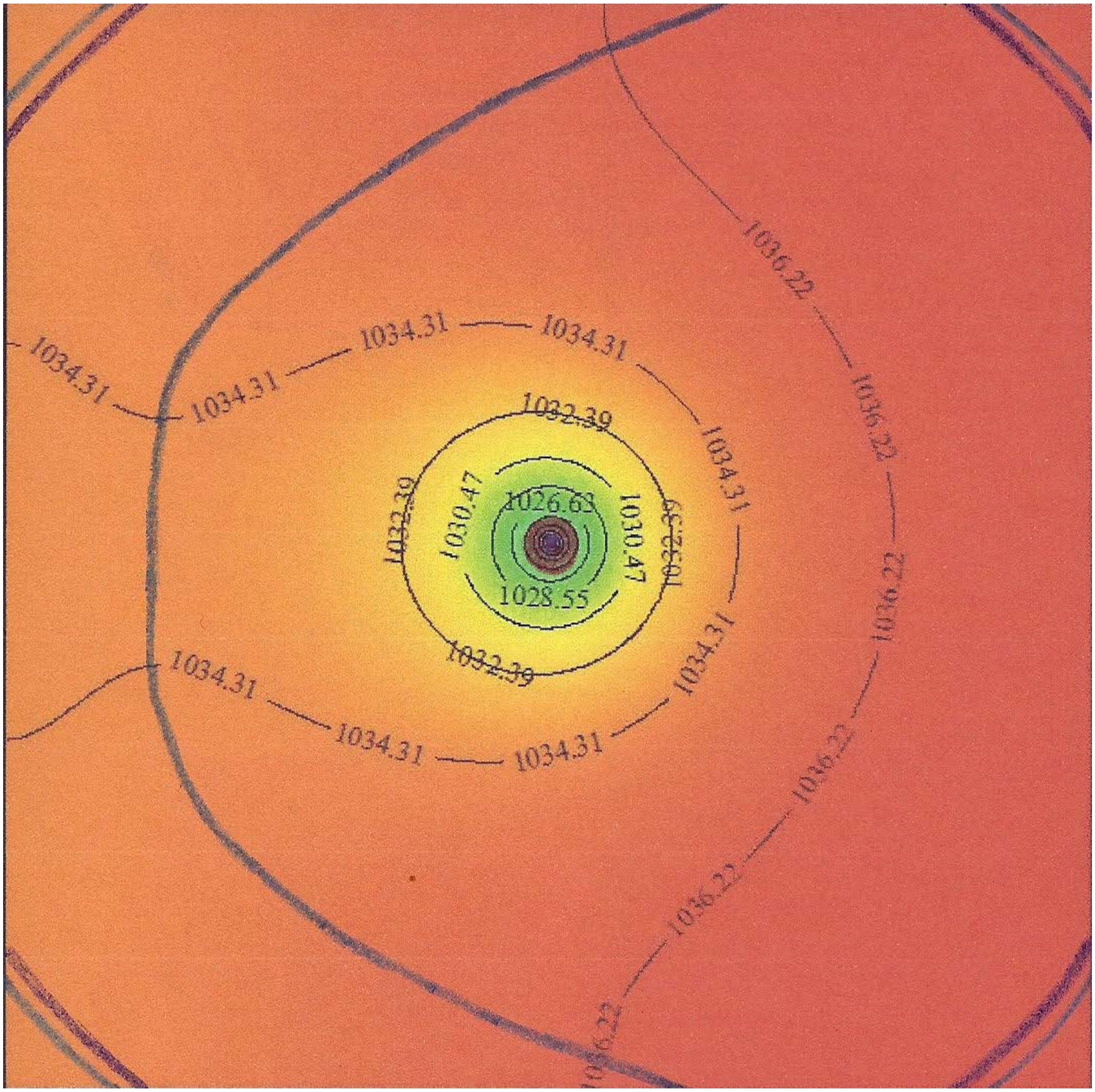


Figure 73. Diagram utilizing HI 2 MODFLOW results from 30 day pumping time as base. Red area in center of model around wellhead is current 100 ft. ADH protection area. Blue line delineates the visible portion of the capture zone as determined by MODFLOW where X_{L30day} equals 1,480 ft. Curves drawn in corners of image indicate Cordova radius of 2,500 ft. and X_L calculated radius of 2,592 ft.



V. CONCLUSTIONS AND RECCOMENDATIONS

Regardless of the model type, a model is just that, a model. A model is a simplification, a method to better understand vastly dynamic situations. A model is also only as appropriate as the accuracy of the information used to build it. Vast differences are observable when comparing results from the analytical models and MODFLOW models even though inputs are relatively consistent.

As expected, aquifer thickness has a large influence on MODFLOW modeling results when modeling deeper wells with no influence from surface water bodies. Coupled with issues regarding recharge values, general head boundaries, and how MODFLOW processes the data, the deeper well model results are questionable. It is unknown how large the cone of depression would be at steady state for the deeper wells. However, a fixed radius protection area appears to be appropriate for the deeper wells based on of the results of the MODFLOW models. This is because all the wells eventually obtain a nearly circular cone of depression. It is up to regulatory agencies to determine what level of protection is desired for these deeper wells and thus determine the capture zone radius. However, the current ADH protection radius is exceedingly small compared to even the one day results of the MODFLOW model or any of the numeric model results.

The results of this study indicate that, for deeper wells with no surface water influence, MODFLOW modeling does not necessarily yield more useful results than analytical modeling. Capture zone shape is drastically different than radii results for shorter modeling times; however as pumping time lengthens, the capture zone becomes more rounded around the wellhead. Some analytical model results did seem to give a much smaller radius of influence than was determined by the computer model. The considerable amount of time necessary for MODFLOW modeling would not be wisely used for establishing capture zones in these types of scenarios.

However, when there is a question as to whether surface water may be impacting well water, MODFLOW modeling can provide definitive answers. Analytical modeling may indicate that a cone of depression intercepts a surface water body. However, analytical modeling does little to indicate the extent of augmentation from surface water to the aquifer when a pumping well is involved. This type of information would be valuable in situations where contaminants entering a surface water body could potentially impact a well.

Given the knowledge of how a small stream, such as Calico Creek in the MODFLOW modeling of the CR 1 well, can greatly influence aquifer flow conditions gives insight on additional work that could be completed. For future work it would be reasonable to consider modeling well HI 5 again with the addition of a stream boundary since it has a significant stream nearby. Also, wells CR 2 and CR 4 could be modeling again with stream boundaries to represent the effect of nearby intermittent streams. If it was found that those wells had surface water augmentation then capture zones and subsequent wellhead protection measures for the wells would need to be adjusted.

Model results are entirely dependent upon the data utilized for development of the models. Therefore, it is pertinent to search out the best hydrologic data available for each water supply well. Unfortunately, for many water supply wells and areas of the state, accurate and appropriate data are sorely lacking. Thus it would be useful in the future for the ADH or Arkansas Geological Survey to have additional aquifer testing performed and hydrologic data collected when new wells are constructed, especially in areas of the state where there is a lack of information regarding the aquifer's hydrologic properties. Pump tests performed on individual sections of the open borehole of a well would be useful to determine the distribution of hydraulic conductivity in the formations and could also be useful for developing more productive water supply wells in the future. Also, when a production well is taken out of service for maintenance or other reasons, hydraulic testing could be performed and the construction properties of the well could be checked since they too have impact on model results and protection assessment.

Testing individual water samples taken from discrete sections of the aquifer could indicate portions of the aquifer that should be cased off to prevent water of poor quality from entering the water supply system. The water samples could also be analyzed to determine rock characteristics present in the aquifer. Potentially, the age of the water could also be determined which could be indicative of travel times through the aquifer system. The financial costs of these sorts of testing would be tempered with the great benefit of more appropriate protection of a municipalities' drinking water supply.

Ultimately, each water supply well should be treated individually. However, wells with similar characteristics can be used as sources of information for other wells that lack data. All models have some usefulness regarding establishing capture zones, but, as with all things, using time and resources wisely should always be considered.

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VII. APPENDIX

A. WELL CONSTRUCTION REPORTS

Well construction report for well near Beaver Lake Dam

STATE OF ARKANSAS
REPORT OF WATER WELL CONSTRUCTION

1 CONTRACTOR Name and number Schell Drilling Co, Inc. C. 1215
DRILLER Name and number McConaughy D. 2430

2 LOCATION / IDENTIFICATION DATE WELL COMPLETED 7-18-88 NEW WELL ☒ WORK-OVER ☐

(a) COUNTY	(b) FRACTION	(c) SECTION	(d) TOWNSHIP	(e) RANGE
Carroll	SE ¼ of NW ¼ of	2	20	27

(f) LOCATE WITH 'X' IN SECTION BELOW

(g) SKETCH MAP

(h) OWNER OF WELL: Corp of Engineers
NAME 700 West Capitol
STREET ADDRESS Little Rock Ar. 72203
CITY

(i) OPERATOR:
NAME
STREET ADDRESS
CITY

3 DESCRIPTION OF FORMATION: DEPTHS IN FEET

	FROM	TO
Over Burden	0	26
Dolomite	26	553
Roubidoux	553	630

ATTACH ADDITIONAL SHEETS IF NECESSARY

4 TOTAL DEPTH OF WELL 630 ft

5 WATER PRODUCING FORMATION? Jeff City + Roubidoux

6 STATIC WATER LEVEL + 2.5 Ft below land surface

7 WATER PRODUCTION RATE WELL PRODUCTS 150 gallons per ☒ min ☐ hr

8 DIAMETER OF BORE HOLE

9 CASING FROM 30 TO +1 W/ 10.37 "ID
FROM " TO +2 W/ 6.65 "ID
TYPE CASING Steel

10 SCREEN:
TYPE DIA SLOT/GA
SET BETWEEN ft and ft
TYPE DIA SLOT/GA
SET BETWEEN ft and ft

11 GRAVEL PACK FROM ft and ft

12 BACK FILLED WITH
FROM ft to ft

13 SEALED WITH Cement
FROM 206 ft to Top ft
FROM ft to ft Pressure Grouted

14 DISINFECTED WITH: HTH + Purex

15 USE OF WELL:
SOURCE WELL ☐ RETURN WELL ☐
A/C CLOSED LOOP ☐ A/C OPEN LOOP ☐

16 PURPOSE:
DOMESTIC ☐ MUNICIPAL ☐
COMMERCIAL ☐ TEST WELL ☐
OIL AND GAS ☐ MONITOR ☐
AGRI/IRRIGATION ☐ PUBLIC SUPPLY ☒
OTHER ☐

17 (For A/C only) WILL SYSTEM ALSO BE USED FOR PURPOSES OTHER THAN A/C? YES ☐ NO ☐
(IF YES NAME USE)

18 (For A/C only) INTO WHAT MEDIUM IS WATER RETURNED?

19 REMARKS:
Flowing 14 GPM

20 SIGNED Willy Schell DATE 8-9-88

RECEIVED OCT 6 - 1988 WATER WELL CONSTRUCTION COMMITTEE ON

AWD-4 JAN 1986 Committee on Waterwell Construction, 2915 South Pine, Little Rock, AR 72204

059134 MAY 18 2013

GEOLOGY COPY

Well construction report for Well HI 1.

Sec. 17 T21N R26W

STATE OF ARKANSAS

Report of Water Well Construction

County in which well is located: CARROLL Co.

WELL # 1

(Please print or type)

OWNER OF WELL HOLIDAY ISLAND SUBURAN Improvement DIST.

WELL CONTRACTOR RAPID DRILLING, INC.

CONTRACTOR LICENSE NO. C-1201

NAME OF DRILLER JOHN GELLER

DRILLER REGISTRATION NO. D-2406

DATE WELL WAS COMPLETED Dec 15, 1970 (MO. DAY YR.)

Well is near STATE Rt 21 road, approximately 7 miles N (NE) E SE S SW W NW of EUREKA SPRINGS, ARK. (TOWN, ETC.)

Directions for reaching well: (use permanent landmarks) 50 YRDS N.W. RANCHHOUSE HOLIDAY ISLANDS

1. Total Depth of Well 1063'
2. Water Producing Formation: GUNTHER SAND From 1030 ft. To 1063 ft.
3. Method of Construction: Rotary ✓ Cable ___ Driven ___ Jetted ___ Bored ___ Dug ___
4. Water Level Below Land Surface 60' ft.
5. Gallons per Hour 30,500
6. Quality of Water: GOOD ✓ SULPHUR ___ IRON ___ GAS ___ OIL ___ OTHER ___
7. Cased to 500 ft. with 25 # PerFT Diameter 8" ID Casing
8. Cemented from 500 ft. to SURFACE ft.
9. Casing Perforated from — ft. to — ft.
10. Well Backfilled with: — from ___ ft. to ___ ft. (SAND, CLAY, CEMENT, MUD)
11. Gravel Pack from — ft. to — ft.
12. Screen Diameter: — inches from — ft. to — ft.
13. Type Screen — Fittings — Slot Size —
14. Use of Well: DOMESTIC ___ IRRIGATION ___ MUNICIPAL ✓ OTHER ___

HALL 'BURTON PRESSURE ... TED

Description and Color of Formation: (Sand, Shale, Sandstone, etc.)	Depths in Feet From	To
SAMPLES & DISCRIPTION		
ON File with ARK GEOLOGICAL COMMISSION		

Remarks: APROX 6' to SOLID LIME. EXPERIENCED NO CRACKS, CREVISES, or OPENINGS to Bottom of HOLE.

Signed: Rapid Drilling Inc., Dale S. Scott Pres.

Date: 1/5/71 (MONTH DAY YEAR)

Mail to: Committee on Water Well Construction – Room 151, State Capitol – Little Rock, Arkansas 72203

GEOLOGY COPY

058666

MAY 17 2013

Well construction report for Well HI 2.

Well #2

Sec 15 T21N R26W

STATE OF ARKANSAS

Report of Water Well Construction

County in which well is located: CARROLL

(Please print or type)

OWNER OF WELL: HOLIDAY ISLAND SUBURBAN DIST

WELL CONTRACTOR: RAPID DRILLING INC.

CONTRACTOR LICENSE NO.: C-1206

NAME OF DRILLER: JOHN GELLER

DRILLER REGISTRATION NO.: D-2406

DATE WELL WAS COMPLETED: Dec 18 (MO.) (DAY) 1970 (YR.)

Well is near STATE LINE RD. road, approximately 7 miles N NE E SE S SW W (NW) of Eureka Springs (TOWN, ETC.) ARK.

Directions for reaching well: (use permanent landmarks)

1. Total Depth of Well: 1128'
2. Water Producing Formation: GUNTHER SAND — From 1100 ft. To 1128 ft.
3. Method of Construction: Rotary ✓ Cable ___ Driven ___ Jetted ___ Bored ___ Dug ___
4. Water Level Below Land Surface: 60' ft.
5. Gallons per Hour: 30,000
6. Quality of Water: GOOD ✓ SULPHUR ___ IRON ___ GAS ___ OIL ___ OTHER ___
7. Cased to 500 ft. with #25 Diameter 8" ID STEEL Casing
8. Cemented from 500 ft. to 0 ft.
9. Casing Perforated from — ft. to — ft.
10. Well Backfilled with: ___ from ___ ft. to ___ ft. (SAND, CLAY, CEMENT, MUD)
11. Gravel Pack from ___ ft. to ___ ft.
12. Screen Diameter: ___ inches from ___ ft. to ___ ft.
13. Type Screen ___ Fittings ___ Slot Size ___
14. Use of Well: DOMESTIC ___ IRRIGATION ___ MUNICIPAL ✓ OTHER ___

Description and Color of Formation: (Sand, Shale, Sandstone, etc.)	Depths in Feet From	To
SAMPLES & DISCRIPTION ON FILE WITH ARK GEOLOGICAL COMM.		

Remarks:

Signed: Rapid Drilling Inc. Dale S. Lett Pres.

Date: 1/5/70 (MONTH) (DAY) (YEAR)

Mail to: Committee on Water Well Construction – Room 151, State Capitol – Little Rock, Arkansas 72203

GEOLOGY COPY

U58665

Well construction report for Well HI 3.

Sec. 16 T21N R26W.

STATE OF ARKANSAS

Report of Water Well Construction

County in which well is located: Carell

(Please print or type)

WELL #3

OWNER OF WELL Holiday Island Development Dist

WELL CONTRACTOR Rapid Drilling Inc.

CONTRACTOR LICENSE NO. C-1201

NAME OF DRILLER Dale T. Lett

DRILLER REGISTRATION NO. D-2407

DATE WELL WAS COMPLETED 10 (MO.) 5 (DAY) 71 (YR.)

Well is near ______ road, approximately 7 miles N NE E SE S SW W NW of Eureka Springs (TOWN, ETC.)

Directions for reaching well: (use permanent landmarks) Contact Crafton & Tull Eng Rogers Ark. for precise map location.

1. Total Depth of Well 1270'
2. Water Producing Formation: Gunter Sand From 1250 ft. To 1270 ft.
3. Method of Construction: Rotary ✓ Cable ___ Driven ___ Jetted ___ Bored ___ Dug ___
4. Water Level Below Land Surface ? ft.
5. Gallons per Hour Estimated 400 G.P.M.
6. Quality of Water: GOOD ✓ SULPHUR ___ IRON ___ GAS ___ OIL ___ OTHER ___
7. Cased to 500 ft. with 8 5/8 OD Diameter Welded 25# Per Foot Casing
8. Cemented from 500 ft. to Surface ft.
9. Casing Perforated from No ft. to — ft.
10. Well Backfilled with: Cement (SAND, CLAY, CEMENT, MUD) from ___ ft. to ___ ft.
11. Gravel Pack from — ft. to — ft.
12. Screen Diameter: — inches from — ft. to — ft.
13. Type Screen — Fittings — Slot Size —
14. Use of Well: DOMESTIC ___ IRRIGATION ___ MUNICIPAL ✓ OTHER ___

Description and Color of Formation: (Sand, Shale, Sandstone, etc.) — Depths in Feet From To

Samples every 5' sent to Arkansas Geological Comm.

Remarks: Encountered no drilling problems - Excellent condition - Cement was circulated without problem.

Signed: Dale T. Lett

Date: 10-15-71 (MONTH DAY YEAR)

Mail to: Committee on Water Well Construction – Room 151, State Capitol – Little Rock, Arkansas 72203

058664 MAY 17 2013

GEOLOGY COPY

Well construction report for Well HI 4.

Well #4

STATE OF ARKANSAS
Report of Water Well Construction

NEW WELL [X] REPLACEMENT WELL [ ]

County in which well is located: CARROLL

(Please print or type)

OWNER OF WELL: Holiday Island SUBURBAN IMPROVEMENT DISTRICT

WELL CONTRACTOR: Layne Western Co. Inc. (MARLEY Co.)

CONTRACTOR LICENSE NO.: 344

NAME OF DRILLER: C. D. Mitchell - Phil Harris

DRILLER REGISTRATION NO.: #346 & #345

DATE WELL WAS COMPLETED: June (MO.) ____ (DAY) 1972 (YR.)

Well is near ____ road, approximately ____ miles N NE E SE S SW W NW of NE¼, SE¼, NE¼ (TOWN, ETC.)

Section 27, Township 21 N., Range 26 W.

Directions for reaching well: (use permanent landmarks) ELEV. 1530 FT.

1. Total Depth of Well: 1880
2. Water Producing Formation: From 7035 ft. To 1860 ft.
3. Method of Construction: Rotary ✓ Cable ____ Driven ____ Jetted ____ Bored ____ Dug ____
4. Water Level Below Land Surface: 520 ft.
5. Gallons per Hour ____ Gallons per Minute ____
6. Well disinfected with: 16 # HTH Tablets
7. Cased to 513' ft. with 13 3/8 Diameter Steel Casing
8. Cemented from 513' ft. to Surface ft.
9. Casing Perforated from NO ft. to ____ ft.
10. Well Backfilled with: Cement (SAND, CLAY, CEMENT, MUD) from 0 ft. to 513' ft.
11. Gravel Pack from NO ft. to ____ ft.
12. Screen Diameter: ____ inches from ____ ft. to ____ ft.
13. Type Screen ____ Fittings ____ Slot Size ____
14. Use of Well: yes DOMESTIC ____ IRRIGATION ____ MUNICIPAL ____ OTHER ____

Description and Color of Formation: (Sand, Shale, Sandstone, etc.)	Depths in Feet From	To
Red Clay w/ white chert Bolders	0	15
Broken Chert w/ Red + Brown Clay seams	15	150
Yellow stained Lime-Dolo-chert streaks Broken	170	300
Red Clay Seam	300	305
Broken Chert Dolo	305	385
Lime-Dolo-Gray	385	670
Gray + white Lime Dolo-Chert streaks	670	975
Dark Brown Gray Lime-Dolo	975	1035
Broken white Gray Lime Dolo-chert.	1035	1110
Dark + light Gray Lime-Dolo	1110	1155
Broken white + Gray Lime-Chert	1155	1173
Remarks: Lime - Dark yellow water stained	1173	1220
Dark Gray + white Lime-Chert Dolo	1220	1230
Lime Dolo w/ Red clay streaks - Red water	1230	1335
Dark Gray Lime-chert-Dolo.	1335	1460
Broken Lime - Dolo Gray + white	1460	1510
White Sand stone	1510	1547
Light Gray Lime-Dolo	1547	1860
Dark Gray Dolo	1860	1880

Signed: C D Mitchell

Date: June (MONTH) 18 (DAY) 1972 (YEAR)

Mail to: Committee on Water Well Construction — 3815 W. Roosevelt Road — Little Rock, Arkansas 72204

COMMITTEE COPY

FORM NO. WD-1

Well construction report for Well HI 5.

NEW WELL [X] REPLACEMENT WELL [ ]

STATE OF ARKANSAS
Report of Water Well Construction

County in which well is located: Carroll

(Please print or type)

OWNER OF WELL Holiday Island Rural Dist.
WELL CONTRACTOR Layne-Western Company, Inc.
CONTRACTOR LICENSE NO. C-1290
NAME OF DRILLER Philip Harris
DRILLER REGISTRATION NO. D2553
DATE WELL WAS COMPLETED June (MO.) 23 (DAY) 1977 (YR.)

Well is near Highway 23 road, approximately 6 miles N (NE) E SE S SW W NW of Eureka Springs (TOWN, ETC.)
Section 23, Township 21N, Range 26W.
Directions for reaching well: (use permanent landmarks) Go north on 23 from Eureka Springs to Holiday Island. Ask at Holiday Island office for directions.

NW¼, SE¼, 23, T.21N., R.26W.

1. Total Depth of Well 1184'
2. Water Producing Formation: From 500 ft. To 1181 ft.
3. Method of Construction:
Rotary X Cable ___ Driven ___ Jetted ___ Bored ___ Dug ___
4. Water Level Below Land Surface 140 ft.
5. ~~Gallons per Hour~~ Gallons per Minute 500
with pumping level of 211'
6. Well disinfected with HTH
7. Cased to 500 ft. with 10-3/4 Diameter steel Casing
8. Cemented from 500 ft. to 0 ft.
9. Casing Perforated from -- ft. to -- ft.
10. Well Backfilled with: Cement from 500 ft. to 0 ft.
(SAND, CLAY, CEMENT, MUD)
11. Gravel Pack from -- ft. to -- ft.
12. Screen Diameter: -- inches from -- ft. to -- ft.
13. Type Screen ___ Fittings ___ Slot Size ___
14. Use of Well: ___ DOMESTIC ___ IRRIGATION X MUNICIPAL ___ OTHER

Description and Color of Formation: (Sand, Shale, Sandstone, etc.)	Depths in Feet From	To
Lt. Dark Gray lime, chert	0	125
Lt-Dk. gray lime, chert, black shale	125	150
Lt-Dk gray lime, chert	150	560
White sand, lime, lt. dk gray lime, chert	560	570
Lt-Dk. gray lime, chert	570	600
White sand	600	620
Lt.-dk, gray lime, chert	620	680
White sand	680	700
Lt.-Dark gray lime, dolomite, chert	700	1055
White sand, lime boulders	1055	1150

Remarks: Red water - 305
Void - broken - 720-722

Signed:

Date: July (MONTH) 21 (DAY) 1977 (YEAR)

Mail to: Committee on Water Well Construction — 3815 W. Roosevelt Road — Little Rock, Arkansas 72204

RECEIVED
JUL 25 1977
COMMITTEE ON WATER WELL CONSTRUCTION

GEOLOGY COPY No 058642 FORM NO. WWC-1

Well construction report for Well HI 6.

REPORT OF WATER WELL CONSTRUCTION

New Well ✓ Work-over Well ____ Replacement Well ____

Owner of Well HOLIDAY ISLAND

Well Contractor LAYNE - WESTERN CO INC

Driller Name and No. PHILLIP HARRIS 2553

Date Well was Completed 10/7/84

1. Total Depth of Well 1255 Ft.
2. Water Producing Formation: GUNTER From ____ Ft. To ____ Ft.
3. Water Level Below Land Surface 253'
4. Gallons per Hour 30,000
5. Well Disinfected with HTH
6. Casing to 20 Ft.
7. Cased with 16" Diameter STEEL Casing
8. Cemented from 20 Ft. to 0 Ft.
9. Use of Well: Domestic ____ Irrigation ____ Municipal ____ Other ____

County CARROLL (in which well is located)

Well is near SHIELDS Road

Section 23 Township 21N Range 26W

Directions for Reaching Well: AT GROUND (use permanent landmark) STORAGE SOUTH SIDE OF GOLF COURSE

Description and Color of Formation (sand, shale, sandstone, etc.)	Depths in feet from	to
SEE ATTACHED		

Remarks:

Signed: Philip L. Harris Date: 11-13-84

Form No. AWD-3

Mail to: Committee on Water Well Construction, 2915 So. Pine Street, Little Rock, Arkansas 72204

MAY 17 2013

GEOLOGY COPY

No. 058813

Well construction log for Well HI 6.

LOG OF WELL

Ft.	In.	to	Ft.	In.	Formation
0			40		GRAY LIMESTONE - TRACE WEATHERED CHERT
40			45		GRAY LIME - CHERT - TRACES GREEN-BLUE SHALE
45			685		LIGHT-DARK GRAY LIME - CHERT
685			765		DARK-LIGHT GRAY LIME CHERT WHITE SAND
765			815		LIGHT-DARK GRAY LIME - CHERT
815			830		WHITE SAND - DARK - LIGHT GRAY LIME - CHERT
830			840		LIGHT-DARK GRAY LIME - CHERT
840			885		LIGHT-DARK GRAY LIME-CHERT - WHITE SAND
					GREEN SHALE
885			930		LIGHT - DARK GRAY LIME - CHERT - WEATHERED
					LIME - RED STAIN
930			975		LIGHT BROWN - PINK - GRAY LIME - CHERT -
					WEATHERED
975			995		LIGHT - DARK GRAY DOLOMITE
995			1000		GRAY WEATHERED LIME - RED CLAY -
					RED WATER
1000			1050		L-BROWN - PINK LIME - GRAY LIME - CALCITE
					WEATHERED - RED WATER
1050			1195		DARK GRAY DOLOMITE - RED WATER
1195			1235		WHITE SANDSTONE
1235			1255		DARK GRAY DOLOMITE
1255					DRILL TERMINATED

058813B

MAY 17 2013

Well construction report for Well CR 4.

STATE OF ARKANSAS

REPORT OF WATER WELL CONSTRUCTION

New Well ____ Work-over Well X Replacement Well ____

Owner of Well CITY OF CALCO ROCK

Contractor FLIPPIN BROS. C 1108

Driller Name and No. HaROLD FLIPPIN 3228

Date Well was Completed 3-1-82

County IZARD (in which well is located)

Well is near Hwy 56E. City Calco Road

Section ____ Township ____ Range ____

Directions for Reaching Well: ____ (use permanent landmark)

1. Total Depth of Well 650 Ft.
2. Water Producing Formation: From 545' Ft. To 580' Ft. 630'
3. Water Level Below Land Surface 50'
4. Gallons per Hour 37 1/2 G.P.M.
5. Well Disinfected with Chlorine
6. Casing to 80 Ft.
7. Cased with 6 1/4 Diameter Steel Casing
8. Cemented from 0 Ft. to 80 Ft.
9. Use of Well: Domestic ____ Irrigation ____ Municipal X Other ____

Description and Color of Formation (sand, shale, sandstone, etc.)	Depths in feet from	to
DIRT + SANDROCK	0	80
Lime Stone	80	650

Remarks:

Signed: Harold Flippin Date: 3-1-82

Form No. AWD-3

000364

AUG 26 2010

Mail to: Committee on Water Well Construction, 2915 So. Pine Street, Little Rock, Arkansas 72204

GEOLOGY COPY

Well construction report for Well CR 5.

STATE OF ARKANSAS

REPORT OF WATER WELL CONSTRUCTION

New Well ✓ Work-over Well ____ Replacement Well ____

Owner of Well: City of Calico Rock

Contractor: Schell C 1215

Driller Name and No.: McConaughy D2430

Date Well was Completed: 2-14-84

1. Total Depth of Well: 1729 Ft.
2. Water Producing Formation: From 600 Ft. To 1700 Ft.
3. Water Level Below Land Surface: 70
4. Gallons per Hour: 56 GPM @ 600
5. Well Disinfected with: HTH
6. Casing to: 540 Ft.
7. Cased with: 6 5/8 - 19# Diameter steel Casing
8. Cemented from: Haliburton Ft. to ____ Ft.
9. Use of Well: Domestic ____ Irrigation ____ Municipal ✓ Other ____

County: Izard (in which well is located)

Well is near ____ Road

Section ____ Township ____ Range ____

Directions for Reaching Well (use permanent landmark): 1/2 mi on Red Lane off of Hwy 56 in Calico Rock

Description and Color of Formation (sand, shale, sandstone, etc.)	Depths in feet from	to
OB	0	16
St Joe Lime	16	25
Everton Sand	25	100
Dolomite	100	1390
Roubidoux	1390	1640
Limestone	1640	TD

Remarks: 1 ft. opening @ 70'

Signed: Will J. Schell Date: 10-15-84

Form No. AWD-3

Mail to: Committee on Water Well Construction, 2915 So. Pine Street, Little Rock, Arkansas 72204

000305

GEOLOGY COPY

AUG 26 2010

Well construction report for Well CR 6.

STATE OF ARKANSAS
REPORT ON WATER WELL CONSTRUCTION & PUMP INSTALLATION

A 1 Contractor Name & Number: Midwest Hydro Drilling & Service C# 1007
2 Driller Name & Number: Philip E. Luther D# 2236
3 Pump Installer Name & Number: P#
4 Date Well Completed: 09-15-98 New Well ☒ Replace or Work-over ☐

10 LOCATE WITH 'X' IN SECTION BELOW

5 COUNTY	6 FRACTION	7 SECTION	8 TOWNSHIP	9 RANGE
Izard	NE ¼ of SW ¼ of	12	T17N	R11W

LONGITUDE 11 092 ° 08 ' 15 " LATITUDE 11 36 ° 07 ' 00 "

B 1 DESCRIPTION OF FORMATION: DEPTHS IN FEET

See Attached Sheet	FROM	TO

ATTACH ADDITIONAL SHEETS IF NECESSARY

2 TOTAL DEPTH OF WELL 2134 ft
3 DEPTHS TO WATER PRODUCING FORMATIONS 590, 780, 1080, 1370, 1460, 1610, 1890'
4 STATIC WATER LEVEL 314 Ft below land surface
5 YIELD 150 gallons per ☒ min ☐ hr
6 DIAMETER OF BORE HOLE 10 IN

C PUMP REPORT

1 TYPE PUMP: SUBMERSIBLE ☐ TURBINE ☐ JET ☐
2 SETTING DEPTH: FEET
3 BRAND NAME AND SERIAL NUMBERS:
4 RATED CAPACITY gallons per minute
5 TYPE LUBRICATION
6 DROP PIPE OR COLUMN PIPE SIZE
7 WIRE SIZE
8 PRESSURE TANK . . . SIZE, MAKE, MODEL
9 DATE OF INSTALLATION OR REPAIR
10 Is there an abandoned water well on the property? No

D 1 LAND OWNER OR OTHER CONTACT PERSON:
NAME City of Calico Rock
STREET ADDRESS P. O. Box 370
CITY Calico Rock, AR

2 CASING FROM 0 TO 680 W/ 10"ID
FROM 0 TO 73 W/ 14"ID
TYPE CASING: Steel

3 SCREEN N/A
TYPE: DIA SLOT/GA
SET FROM FT TO FT
TYPE: DIA SLOT/GA
SET FROM FT TO FT

4 GRAVEL PACK N/A FROM FT TO FT

5 BACK FILLED WITH:
FROM FT TO FT

6 SEALED WITH: Cement Grout
FROM 0 FT TO 680 FT
FROM FT TO FT

7 DISINFECTED WITH: 20 lbs. HTH

8 USE OF WELL:
DOMESTIC ☐ COMMERCIAL ☐
IRRIGATION ☐ MONITOR ☐
LIVESTOCK/POULTRY ☐ TEST WELL ☐
OIL/GAS SUPPLY ☐ SEMI-PUBLIC ☐
PUBLIC SUPPLY ☒ OTHER

(A/C HEATPUMP TYPE WELLS)
SOURCE ☐ RETURN ☐
CLOSED LOOP ☐

9 (For A/C only) Will system also be used for purposes other than Heating or Air Conditioning?
If yes, name use: yes ☐ no ☐

10 (For A/C open-loop only) Into what medium is water returned?

11 REMARKS

12 SIGNED [signature] DATE 9-30-98

AWD-7 JAN 89 Arkansas Water Well Construction Commission, 101 East Capitol, Suite 350, Little Rock, AR 72201
ACI-5945

AUG 26 2010

000109

GEOLOGY COPY

Well construction log for Well CR 6.

Midwest Hydro
Drilling & Service, Inc.
1297 Gravois
St. Clair, Mo. 63077
(314) 629-2424

City of Calico Rock
Drillers Log Well #6
Project # 96-075-3
ADH ID # 2521/11-12,Ref # 98-19623
Updated 7-9-1998

62' - 118'	Grey limestone
118' - 139'	Grey limestone
139' - 241'	Dark grey & light grey limestone
241' - 278'	Dark grey limestone
278' -282'	Broken grey limestone
282' - 386'	Grey limestone
386' - 414'	Dark grey & light grey limestone
414' - 529'	Dark grey limestone
529' - 586'	Dark grey & dark brown dolomite
586' - 588'	Broken grey dolomite w/chert
588' - 590'	Gray limestone
590' - 596'	Broken grey limestone, low vol. water
596' - 700'	Grey dolomite w/chert
700' - 780'	Dark brown dolomite
780' - 1080'	Dark grey & light grey dolomite w/chert, more water
1080' - 1370'	Dark grey dolomite with chert more water
1370' - 1460'	Light gray dolomite with chert more water
1460' - 1610'	Gray dolomite with sandstone, more water
1610' - 1890'	Light gray dolomite with chert and sandstone
1890' - 1960'	Light and medium gray dolomite with chert
1960' - 2080'	Dark gray dolomite with chert more water
2080' - 2134'	Gray dolomite with chert and sandstone, more water
2134' - 2200'	Total depth

Well construction report for Calico Rock well that had to be abandoned due to high water table.

STATE OF ARKANSAS
REPORT ON WATER WELL CONSTRUCTION & PUMP INSTALLATION

A

1 Contractor Name & Number: Washington Pump Co. C# 1030

2 Driller Name & Number: ~~Stephen Washington~~ D# ~~[illegible]~~

3 Pump Installer Name & Number: Randy Washington P# 4068

4 Date Well Completed: 3-16-99 New Well ☐ Replace or Work-over ☑ 2363

5 COUNTY	6 FRACTION		7 SECTION	8 TOWNSHIP	9 RANGE
Izard	SE ¼ of	NW ¼ of	11	17	11

10 LOCATE WITH 'X' IN SECTION BELOW

11 LONGITUDE 36 ° 07 ' 46 "

11 LATITUDE 92 ° 07 ' 48 "

B

1 DESCRIPTION OF FORMATION:	DEPTHS IN FEET FROM	TO
Grouted from bottom (63') to top. 3 yds Neat Crete. water level was at 3'		

ATTACH ADDITIONAL SHEETS IF NECESSARY

2 TOTAL DEPTH OF WELL 63' ft

3 DEPTHS TO WATER PRODUCING FORMATIONS. Not known

4 STATIC WATER LEVEL 3 Ft below land surface

5 YIELD Not known gallons per ☐ min ☐ hr

6 DIAMETER OF BORE HOLE IN

C PUMP REPORT

1 TYPE PUMP: SUBMERSIBLE ☐ TURBINE ☐ JET ☐

2 SETTING DEPTH: FEET

3 BRAND NAME AND SERIAL NUMBERS:

4 RATED CAPACITY gallons per minute

5 TYPE LUBRICATION

6 DROP PIPE OR COLUMN PIPE SIZE

7 WIRE SIZE

8 PRESSURE TANK . . . SIZE, MAKE, MODEL

9 DATE OF INSTALLATION OR REPAIR

10 Is there an abandoned water well on the property?

Abandoned

D

1 LAND OWNER OR OTHER CONTACT PERSON:

NAME City of Calico Rock

STREET ADDRESS PO Box 370

CITY Calico Rock, Ar 72519

2 CASING FROM TO W/ "ID

FROM TO W/ "ID

TYPE CASING:

3 SCREEN

TYPE: DIA SLOT/GA

SET FROM FT TO FT

TYPE: DIA SLOT/GA

SET FROM FT TO FT

4 GRAVEL PACK FROM FT TO FT

5 BACK FILLED WITH:

FROM FT TO FT

6 SEALED WITH:

FROM FT TO FT

FROM FT TO FT

7 DISINFECTED WITH:

8 USE OF WELL:

DOMESTIC	☐	COMMERCIAL	☐
IRRIGATION	☐	MONITOR	☐
LIVESTOCK/POULTRY	☐	TEST WELL	☐
OIL/GAS SUPPLY	☐	SEMI-PUBLIC	☐
PUBLIC SUPPLY	☒	OTHER	

(A/C HEATPUMP TYPE WELLS)

SOURCE ☐ RETURN ☐

CLOSED LOOP ☐

9 (For A/C only) Will system also be used for purposes other than Heating or Air Conditioning?

If yes, name use: yes ☐ no ☐

10 (For A/C open-loop only) Into what medium is water returned?

11 REMARKS

12 SIGNED Randy Washington DATE 4-6-99

AWD-7 JAN 89
ACI-5945

Arkansas Water Well Construction Commission, 101 East Capitol, Suite 350, Little Rock, AR 72201

000023 AUG 26 2010

GEOLOGY COPY

B. AQUIFER TEST RESULTS

HI 1 data input for well.

Pumping Test - Water Level Data		Page 1 of 1
Project: Holiday Island well 1		
Number:		
Client:		
Location:	Pumping Test: Pumping Test 1	Pumping Well: Well 1
Test Conducted by:	Test Date: 3/6/2014	Discharge Rate: 600 [U.S. gal/min]
Observation Well: Well 1	Static Water Level [ft]: 0.00	Radial Distance to PW [ft]: -

	Time [min]	Water Level [ft]	Drawdown [ft]
1	6.1917	41.10	41.10
2	13.7858	45.10	45.10
3	57.665	50.10	50.10
4	109.9512	53.10	53.10
5	357.0467	56.10	56.10
6	613.1066	60.10	60.10
7	1310.8066	62.10	62.10
8	1667.9881	65.10	65.10
9	2110.4963	65.10	65.10
10	2655.9923	67.10	67.10
11	3325.2567	68.10	68.10
12	4142.6511	68.10	68.10
13	5136.634	68.10	68.10

HI 1 data input for observation well.

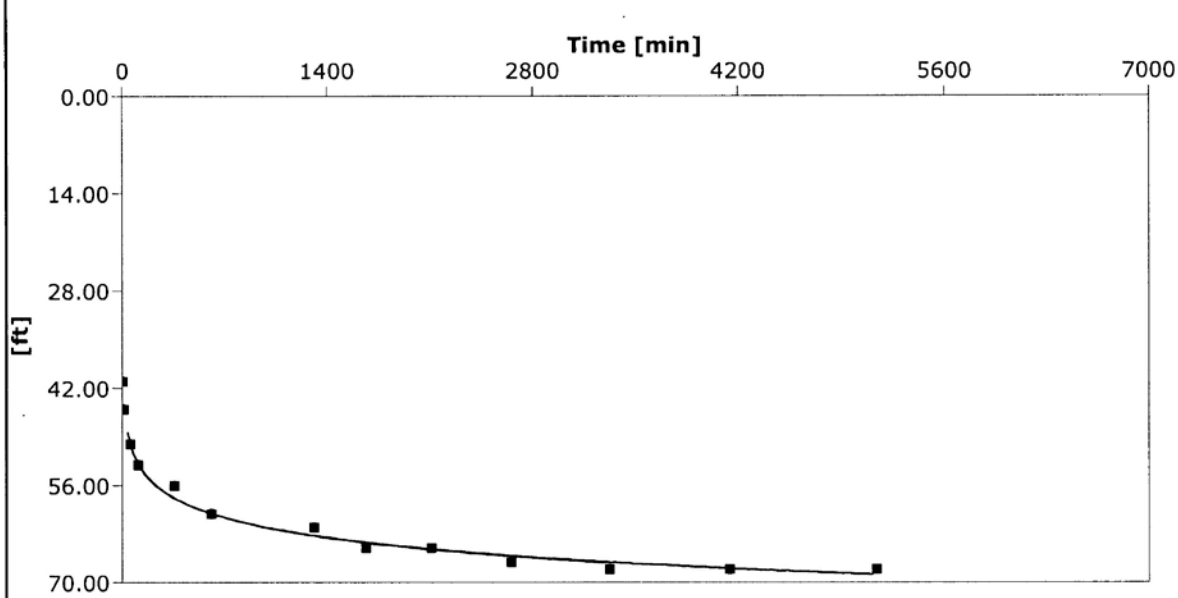
Pumping Test - Water Level Data		Page 1 of 1
Project: Holiday Island well 1		
Number:		
Client:		
Location:	Pumping Test: Pumping Test 1	Pumping Well: Well 1
Test Conducted by:	Test Date: 3/6/2014	Discharge Rate: 600 [U.S. gal/min]
Observation Well: Well 2	Static Water Level [ft]: 0.00	Radial Distance to PW [ft]: 1.41

	Time [min]	Water Level [ft]	Drawdown [ft]
1	6.1917	41.00	41.00
2	13.7858	45.00	45.00
3	57.665	50.00	50.00
4	109.9512	53.00	53.00
5	357.0467	56.00	56.00
6	613.1066	60.00	60.00
7	1310.8066	62.00	62.00
8	1667.9881	65.00	65.00
9	2655.9923	67.00	67.00
10	3325.2567	68.00	68.00

HI 1 result of Theis solver.

	Pumping Test Analysis Report
	Project: Holiday Island well 1
	Number:
	Client:

Location:	Pumping Test: Pumping Test 1	Pumping Well: Well 1
Test Conducted by:		Test Date: 3/6/2014
Analysis Performed by:	New analysis 1	Analysis Date: 3/6/2014
Aquifer Thickness: 563.00 ft	Discharge Rate: 600 [U.S. gal/min]	



Calculation using Theis

Observation Well	Transmissivity [ft²/d]	Hydraulic Conductivity [ft/d]	Storage coefficient	Radial Distance to PW [ft]	
Well 1	2.22×10^{3}	3.95×10^{0}	9.25×10^{-3}	0.34	
Well 2	2.20×10^{3}	3.90×10^{0}	6.07×10^{-4}	1.41	
Average	2.21×10^{3}	3.93×10^{0}	4.93×10^{-3}		

HI 1 summary of methods tested.

				Pumping Test Analysis Report				
				Project: Holiday Island well 1				
				Number:				
				Client:				
Location:			Pumping Test: Pumping Test 1			Pumping Well: Well 1		
Test Conducted by:						Test Date: 3/6/2014		
Aquifer Thickness: 563.00 ft			Discharge Rate: 600 [U.S. gal/min]					
	Analysis Name	Analysis Performed by	Analysis Date	Method name	Well	T [ft²/d]	K [ft/d]	S
1	New analysis 1		3/6/2014	Theis	Well 1	2.22×10^{3}	3.95×10^{0}	9.25×10^{-3}
2	New analysis 1		3/6/2014	Theis	Well 2	2.20×10^{3}	3.90×10^{0}	6.07×10^{-4}
3	New analysis 2		3/6/2014	Cooper & Jacob I	Well 1	2.22×10^{3}	3.94×10^{0}	9.26×10^{-3}
4	New analysis 2		3/6/2014	Cooper & Jacob I	Well 2	9.30×10^{2}	1.65×10^{0}	1.00×10^{-4}
5	New analysis 3		3/6/2014	Neuman	Well 1	2.22×10^{3}	3.95×10^{0}	1.88×10^{-1}
6	New analysis 3		3/6/2014	Neuman	Well 2	9.30×10^{2}	1.65×10^{0}	1.00×10^{-4}
7	New analysis 4		3/20/2014	Double Porosity	Well 1	2.22×10^{3}	3.95×10^{0}	2.65×10^{-3}
8	New analysis 4		3/20/2014	Double Porosity	Well 2	9.30×10^{2}	1.65×10^{0}	1.00×10^{-4}
9	New analysis 5		3/20/2014	Moench Fracture Flow	Well 1	2.22×10^{3}	3.95×10^{0}	4.36×10^{-3}
10	New analysis 5		3/20/2014	Moench Fracture Flow	Well 2	9.30×10^{2}	1.65×10^{0}	1.00×10^{-4}
11	New analysis 6		3/20/2014	Cooper & Jacob III	Well 1	2.22×10^{3}	3.94×10^{0}	9.26×10^{-3}
12	New analysis 6		3/20/2014	Cooper & Jacob III	Well 2	2.64×10^{5}	4.69×10^{2}	1.00×10^{-29}
13	New analysis 7		3/20/2014	Papadopulos & Cooper	Well 1	2.24×10^{3}	3.97×10^{0}	8.41×10^{-3}
14	New analysis 7		3/20/2014	Papadopulos & Cooper	Well 2	9.30×10^{2}	1.65×10^{0}	1.00×10^{-4}

HI 4 data input for well.

	Pumping Test - Water Level Data	Page 1 of 1
	Project: Holiday Island well 4	
	Number:	
	Client:	
Location:	Pumping Test: Pumping Test 1	Pumping Well: Well 1
Test Conducted by:	Test Date: 3/6/2014	Discharge Rate: 502 [U.S. gal/min]
Observation Well: Well 1	Static Water Level [ft]: 0.00	Radial Distance to PW [ft]: -

	Time [min]	Water Level [ft]	Drawdown [ft]
1	1	45.00	45.00
2	13.7858	65.00	65.00
3	57.665	70.00	70.00
4	613.1066	77.00	77.00
5	2655.9923	80.00	80.00
6	6340.3381	82.00	82.00
7	9536.7432	84.00	84.00
8	20589.1132	85.00	85.00

HI 4 data input for observation well.

Pumping Test - Water Level Data	Page 1 of 1
Project: Holiday Island well 4	
Number:	
Client:	

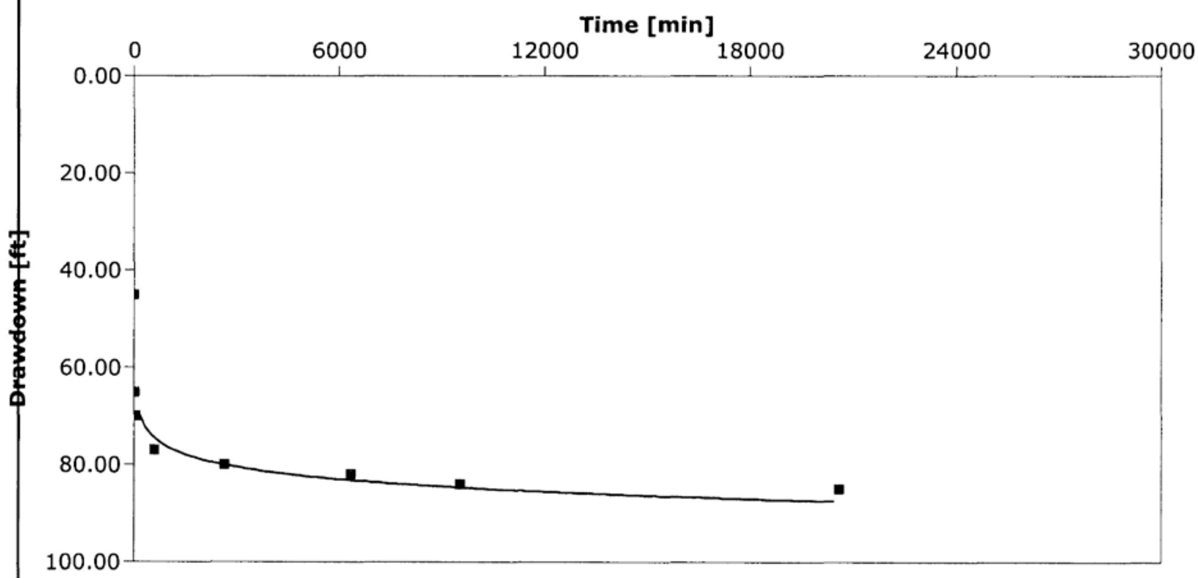
Location:	Pumping Test: Pumping Test 1	Pumping Well: Well 1
Test Conducted by:	Test Date: 3/6/2014	Discharge Rate: 502 [U.S. gal/min]
Observation Well: Well 2	Static Water Level [ft]: 0.00	Radial Distance to PW [ft]: 1.41

	Time [min]	Water Level [ft]	Drawdown [ft]
1	1	45.00	45.00
2	13.7858	65.00	65.00
3	57.665	70.00	70.00
4	613.1066	77.00	77.00
5	2655.9923	80.00	80.00
6	6340.3381	82.00	82.00
7	9536.7432	84.00	84.00
8	20589.1132	85.00	85.00

HI 4 result of Newman solver.

	Pumping Test Analysis Report
	Project: Holiday Island well 4
	Number:
	Client:

Location:	Pumping Test: Pumping Test 1	Pumping Well: Well 1
Test Conducted by:		Test Date: 3/6/2014
Analysis Performed by:	New analysis 3	Analysis Date: 3/6/2014
Aquifer Thickness: 1367.00 ft	Discharge Rate: 502 [U.S. gal/min]	



Calculation using Neuman

Observation Well	Transmissivity [ft²/d]	Hydraulic Conductivity [ft/d]	Specific Yield	Ratio K(v)/K(h)	Ratio Sy/S	Radial Distance to PW [ft]
Well 1	2.10×10^{3}	1.53×10^{0}	1.08×10^{-2}	7.18×10^{-3}	1.10×10^{3}	0.54
Well 2	9.30×10^{2}	6.80×10^{-1}	1.00×10^{-4}	1.00×10^{-2}	1.00×10^{2}	1.41
Average	1.51×10^{3}	1.11×10^{0}	5.46×10^{-3}	8.59×10^{-3}	6.02×10^{2}	

HI 4 summary of methods tested.

				Pumping Test Analysis Report				
				Project: Holiday Island well 4				
				Number:				
				Client:				
Location:			Pumping Test: Pumping Test 1			Pumping Well: Well 1		
Test Conducted by:						Test Date: 3/6/2014		
Aquifer Thickness: 1367.00 ft			Discharge Rate: 502 [U.S. gal/min]					
	Analysis Name	Analysis Performed by	Analysis Date	Method name	Well	T [ft²/d]	K [ft/d]	S
1	New analysis 1		3/6/2014	Theis	Well 1	1.05×10^{2}	7.65×10^{-2}	
2	New analysis 1		3/6/2014	Theis	Well 2	1.02×10^{2}	7.47×10^{-2}	
3	New analysis 2		3/6/2014	Cooper & Jacob I	Well 1	2.10×10^{3}	1.53×10^{0}	9.80×10^{-6}
4	New analysis 2		3/6/2014	Cooper & Jacob I	Well 2	9.30×10^{2}	6.80×10^{-1}	1.00×10^{-4}
5	New analysis 3		3/6/2014	Neuman	Well 1	2.10×10^{3}	1.53×10^{0}	1.08×10^{-2}
6	New analysis 3		3/6/2014	Neuman	Well 2	9.30×10^{2}	6.80×10^{-1}	1.00×10^{-4}
7	New analysis 4		3/20/2014	Double Porosity	Well 1	2.10×10^{3}	1.53×10^{0}	1.79×10^{-8}
8	New analysis 4		3/20/2014	Double Porosity	Well 2	9.30×10^{2}	6.80×10^{-1}	1.00×10^{-4}
9	New analysis 5		3/20/2014	Moench Fracture Flow	Well 1	9.30×10^{2}	6.80×10^{-1}	1.00×10^{-4}
10	New analysis 5		3/20/2014	Moench Fracture Flow	Well 2	9.30×10^{2}	6.80×10^{-1}	1.00×10^{-4}
11	New analysis 6		3/20/2014	Cooper & Jacob III	Well 1	2.10×10^{3}	1.53×10^{0}	9.80×10^{-6}
12	New analysis 6		3/20/2014	Cooper & Jacob III	Well 2	9.30×10^{2}	6.80×10^{-1}	1.00×10^{-4}
13	New analysis 7		3/20/2014	Papadopulos & Cooper	Well 1	2.54×10^{3}	1.86×10^{0}	1.00×10^{-7}
14	New analysis 7		3/20/2014	Papadopulos & Cooper	Well 2	9.30×10^{2}	6.80×10^{-1}	1.00×10^{-4}

Omaha data input for well.

				Pumping Test - Water Level Data	Page 1 of 1
				Project: Omaha	
				Number:	
				Client:	
Location:			Pumping Test: Pumping Test 1	Pumping Well: Well 1	
Test Conducted by:			Test Date: 3/6/2014	Discharge Rate: 52 [U.S. gal/min]	
Observation Well: Well 1			Static Water Level [ft]: 0.00	Radial Distance to PW [ft]: -	

	Time [min]	Water Level [ft]	Drawdown [ft]
1	57.665	30.00	30.00
2	357.0467	38.00	38.00
3	794.9615	44.00	44.00
4	2655.9923	47.00	47.00
5	4142.6511	49.00	49.00
6	6340.3381	49.50	49.50
7	9536.7432	50.00	50.00

Omaha data input for observation well.

Pumping Test - Water Level Data	Page 1 of 1
Project: Omaha	
Number:	
Client:	

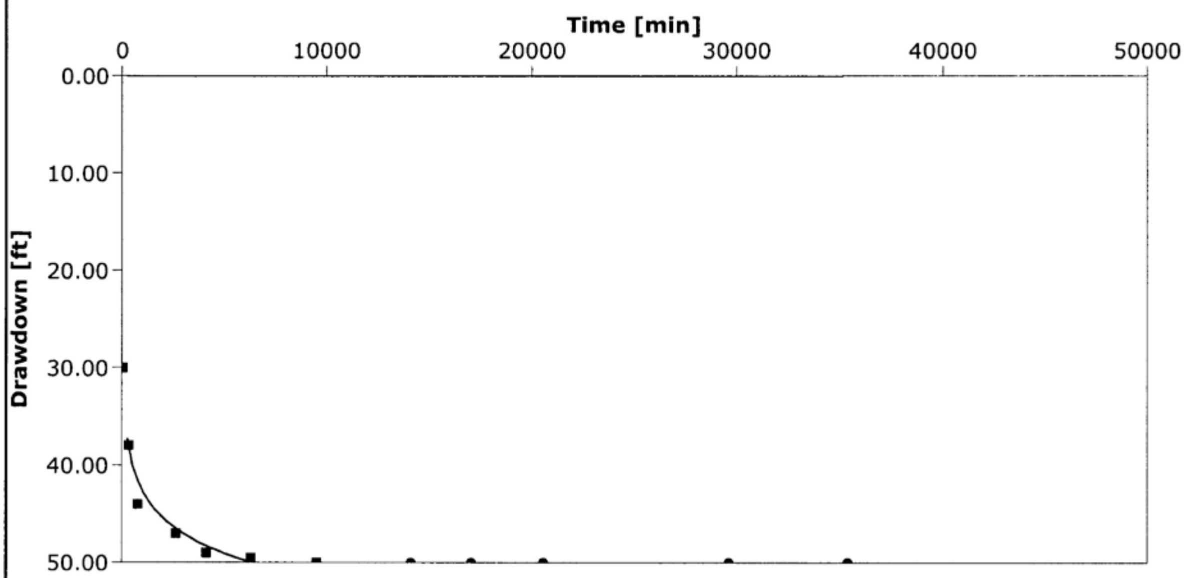
Location:	Pumping Test: Pumping Test 1	Pumping Well: Well 1
Test Conducted by:	Test Date: 3/6/2014	Discharge Rate: 52 [U.S. gal/min]
Observation Well: Well 2	Static Water Level [ft]: 0.00	Radial Distance to PW [ft]: -

	Time [min]	Water Level [ft]	Drawdown [ft]
1	57.665	30.00	30.00
2	357.0467	38.00	38.00
3	794.9615	44.00	44.00
4	2655.9923	47.00	47.00
5	4142.6511	49.00	49.00
6	6340.3381	49.50	49.50
7	9536.7432	50.00	50.00
8	14116.7096	50.00	50.00
9	17078.8545	50.00	50.00
10	20589.1132	50.00	50.00
11	29619.6767	50.00	50.00
12	35354.8175	50.00	50.00

Omaha result of Monech Fracture Flow solver.

	Pumping Test Analysis Report
	Project: Omaha
	Number:
	Client:

Location:	Pumping Test: Pumping Test 1	Pumping Well: Well 1
Test Conducted by:		Test Date: 3/6/2014
Analysis Performed by:	New analysis 5	Analysis Date: 3/20/2014
Aquifer Thickness: 1251.00 ft	Discharge Rate: 52 [U.S. gal/min]	



Calculation using Moench Fracture Flow

Observation Well	Transmissivity [ft²/d]	Hydraulic Conductivity [ft/d]	Storage coefficient	Sigma	Gamma	SF	Radial Distance to PW [ft]
Well 1	1.98×10^{2}	1.58×10^{-1}	2.34×10^{-4}	5.31×10^{2}	1.88×10^{-1}	4.82×10^{0}	0.25
Well 2	9.30×10^{2}	7.43×10^{-1}	1.00×10^{-4}	1.00×10^{2}	1.00×10^{-1}	1.00×10^{0}	
Average	5.64×10^{2}	4.51×10^{-1}	1.67×10^{-4}	3.16×10^{2}	1.44×10^{-1}	2.91×10^{0}	

Omaha summary of methods tested.

	Pumping Test Analysis Report	
	Project: Omaha	
	Number:	
	Client:	
Location:	Pumping Test: Pumping Test 1	Pumping Well: Well 1
Test Conducted by:		Test Date: 3/6/2014
Aquifer Thickness: 1251.00 ft	Discharge Rate: 52 [U.S. gal/min]	

	Analysis Name	Analysis Performed by	Analysis Date	Method name	Well	T [ft²/d]	K [ft/d]	S
1	New analysis 1		3/6/2014	Theis	Well 1	1.98×10^{2}	1.58×10^{-1}	1.25×10^{-1}
2	New analysis 1		3/6/2014	Theis	Well 2	1.71×10^{1}	1.37×10^{-2}	5.89×10^{-2}
3	New analysis 2		3/6/2014	Cooper & Jacob I	Well 1	1.98×10^{2}	1.58×10^{-1}	1.25×10^{-1}
4	New analysis 2		3/6/2014	Cooper & Jacob I	Well 2	9.30×10^{2}	7.43×10^{-1}	1.00×10^{-4}
5	New analysis 3		3/6/2014	Neuman	Well 1	9.30×10^{2}	7.43×10^{-1}	1.00×10^{-4}
6	New analysis 3		3/6/2014	Neuman	Well 2	9.30×10^{2}	7.43×10^{-1}	1.00×10^{-4}
7	New analysis 4		3/20/2014	Double Porosity	Well 1	9.30×10^{2}	7.43×10^{-1}	1.00×10^{-4}
8	New analysis 4		3/20/2014	Double Porosity	Well 2	9.30×10^{2}	7.43×10^{-1}	1.00×10^{-4}
9	New analysis 5		3/20/2014	Moench Fracture Flow	Well 1	1.98×10^{2}	1.58×10^{-1}	2.34×10^{-4}
10	New analysis 5		3/20/2014	Moench Fracture Flow	Well 2	9.30×10^{2}	7.43×10^{-1}	1.00×10^{-4}
11	New analysis 6		3/20/2014	Cooper & Jacob III	Well 1	1.98×10^{2}	1.58×10^{-1}	1.25×10^{-1}
12	New analysis 6		3/20/2014	Cooper & Jacob III	Well 2	9.30×10^{2}	7.43×10^{-1}	1.00×10^{-4}
13	New analysis 7		3/20/2014	Papadopulos & Cooper	Well 1	1.99×10^{2}	1.59×10^{-1}	1.18×10^{-1}
14	New analysis 7		3/20/2014	Papadopulos & Cooper	Well 2	9.30×10^{2}	7.43×10^{-1}	1.00×10^{-4}

C. DIAGRAMS UTILIZED FOR DEVELOPING MODFLOW MODELS

Well HI 1

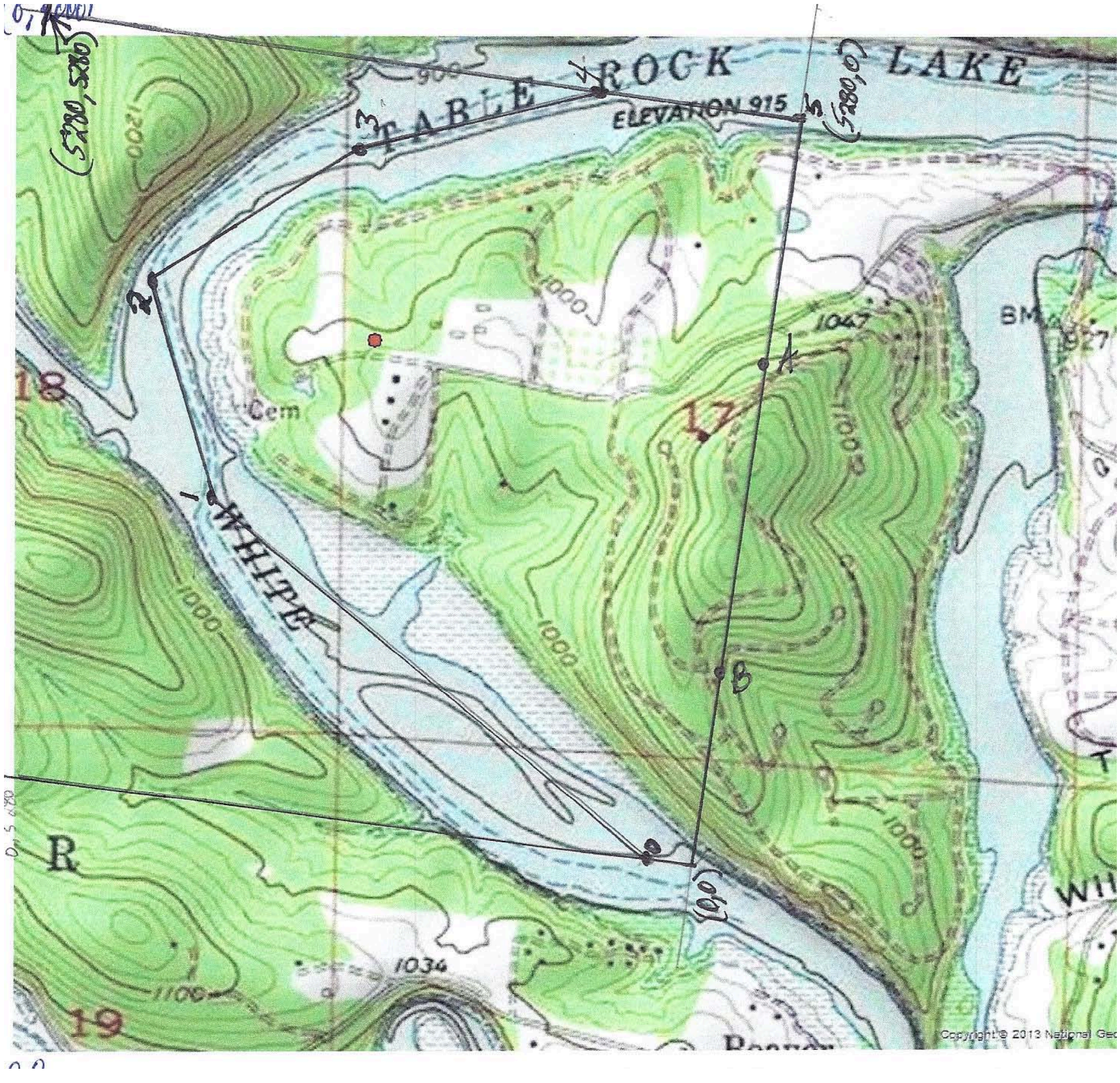
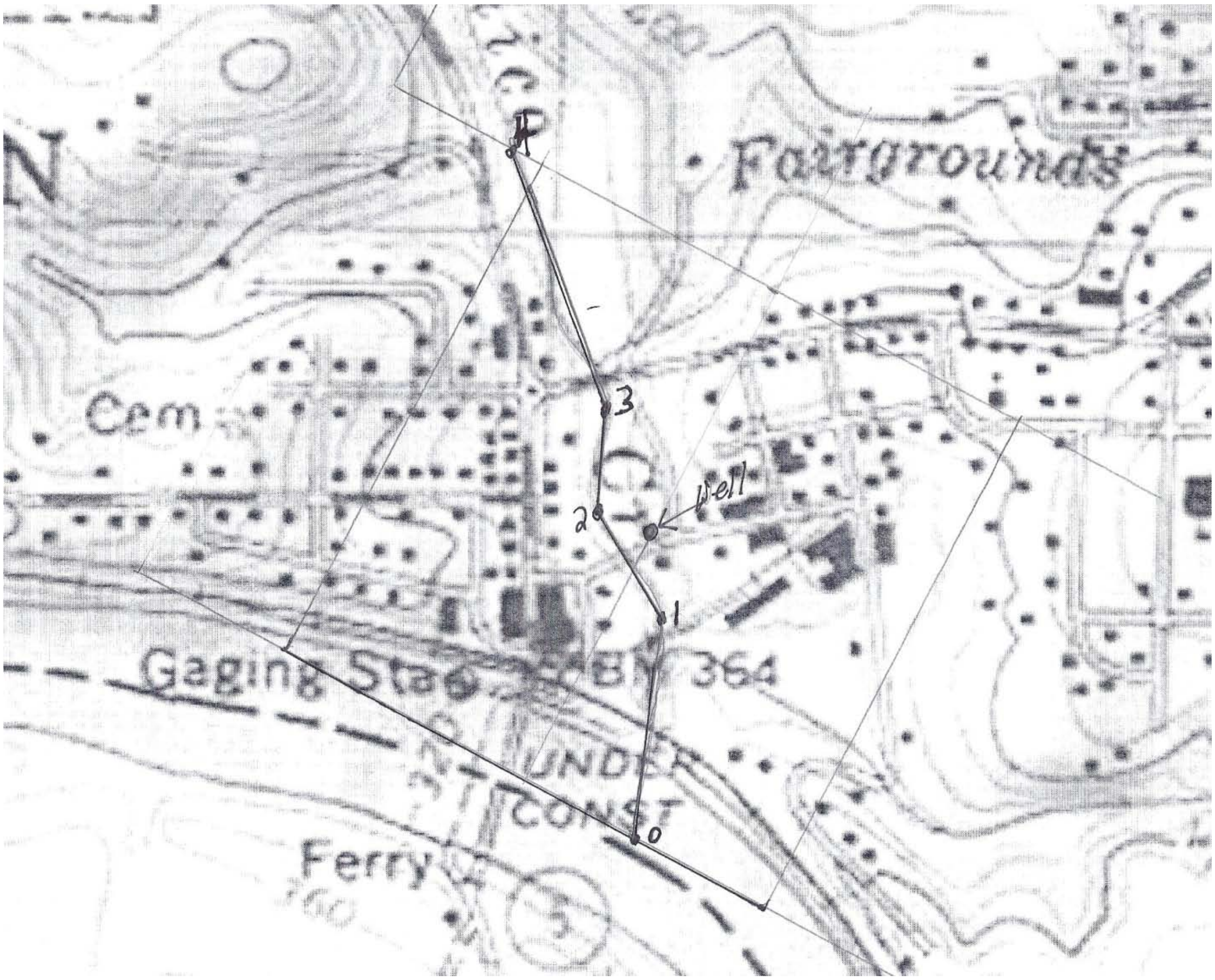


TABLE ROCK LAKE
ELEVATION 915
(5280,5280)
(5880,0)
(0,0)
Cem
BM
1047
1034
18
17
19
R
WHITE
A
B

Well CR 1


Fairgrounds
Cem
Well
Gaging Sta
BM 364
UNDER CONST
Ferry
0
1
2
3
4

D. HI 2 HEAD VALUE DATA

Model Run	X Distance, Feet	Head Value, Feet
1 Day	74	1033.3
1 Day	740	1034.4
1 Day	1258	1035.5
1 Day	1850	1035.5
1 Day	1924	1034.4
1 Day	2035	1018
1 Day	2146	1034.4
1 Day	2220	1035.5
1 Day	2294	1036.6
30 Days	1480	1032.4
30 Days	1702	1030.5
30 Days	1813	1028.6
30 Days	1887	1026.6
30 Days	2035	1009
30 Days	2146	1026.6
30 Days	2479	1032.4
30 Days	2701	1034.3
30 Days	3293	1036.2
90 Days	740	1032.7
90 Days	1295	1030.6
90 Days	1591	1028.5
90 Days	1739	1026.4
90 Days	1924	1022.3
90 Days	2035	1005
90 Days	2146	1022.3
90 Days	2405	1028.5
90 Days	2960	1032.7
90 Days	3885	1034.8
180 Days	925	1030
180 Days	1369	1027.7
180 Days	1776	1023.6
180 Days	1924	1019
180 Days	2035	1003
180 Days	2146	1019
180 Days	2294	1023.6
180 Days	2405	1025.7
180 Days	2960	1030

365 Days	1073	1024
365 Days	1628	1020
365 Days	1924	1013.7
365 Days	2035	997
365 Days	2183	1013.7
365 Days	2405	1020
365 Days	2960	1024
1825 Days	1073	980.5
1825 Days	1443	978.3
1825 Days	1665	976
1825 Days	1850	969.6
1825 Days	2035	952
1825 Days	2183	969.6
1825 Days	2405	976
1825 Days	2627	978.3
1825 Days	2960	980.5
0 Days	0	1033
0 Days	4000	1041